PB-228 946

EXPERIMENTAL BACTERIAL AND CHEMICAL POLLUTION OF WELLS VIA GROUND WATER, AND THE FACTORS INVOLVED

C. W. Stiles, et al

Public Health Service
Washington, D. C.

June 1927

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UNITED STATES PUBLIC HEALTH SERVICE

HYGIENIC LABORATORY BULLETIN No. 147
JUNE, 1927

EXPERIMENTAL BACTERIAL AND CHEMICAL POLLUTION OF WELLS VIA GROUND WATER, AND THE FACTORS INVOLVED

BY

C. W. STILES, H. R. CROHURST, and GORDON E. THOMSON

REPORT ON THE GEOLOGY AND GROUND WATER HYDROLOGY OF THE EXPERIMENTAL AREA OF THE UNITED STATES PUBLIC HEALTH SERVICE AT FORT CASWELL, N. C.

BY

NORAH DOWELL STEARNS

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EXPERIMENTAL BACTERIAL AND CHEMICAL POLLUTION OF WELLS, VIA GROUND WATER, AND THE FACTORS INVOLVED[1]

By C. W. Stiles, Professor of Zoology; H. R. Crohurst, Sanitary Engineer; G. E. Thomson, Laboratory Aide, United States Public Health Service

1. INTRODUCTION

There exists a decided difference of opinion in regard to the distance to which pollution will travel under ground, and the divergent views find legal expression in ordinances and regulations prescribing the minimum distance (p. 91) permissible between a well and a privy.

As experimental study of the problem is tedious, time consuming and expensive, publications on this question are relatively few, and conclusions have not unnaturally been based largely upon epidemiological observations, general reasoning, and examination of conditions found to exist at a given moment, rather than upon experimental production of conditions with study of the results.

The studies presented in the present report are based upon methods of procedure so different from those of the studies by other authors that an historical review of the general literature would not seem to justify drawing comparisons in results. Accordingly, largely in order to meet this point, the present report is confined to our own experimental work, and represents a presentation of new data, the conclusions, and the technique employed.

The work was done under the board on excreta disposal. Prior to the preparation of the report several members of the board visited (June, 1923) the experimental field at Fort Caswell, N. C., studied the methods and the data obtained up to that date, and accepted the evidence presented as respects the extension of the pollution. The following persons were present:

Maj. G. C. Dunham, United States Army, to represent Col. C. F. Craig, United States Army, member of the board.

Surg. L. L. Lumsden, United States Public Health Service, member of the board.

Surg. George W. McCoy, United States Public Health Service, guest of the board.

Prof. Earle B. Phelps, Columbia University, New York, secretary of the board.

Prof. C. W. Stiles, United States Public Health Service, chairman of the board.

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[1] Manuscript submitted for publication, Dec. 1, 192[illegible].

With this [illegible] given in the report

The other members of the board (Col. C. F. Craig, United States Army; Prof. E. O. Jordan, University of Chicago; Dr. W. S. Rankin, North Carolina State Board of Health; and Prof. G. C. Whipple, Harvard University) were unavoidably absent from this meeting, but monthly reports of progress were forwarded to the entire membership.

Data obtained since the board meeting of June, 1923, have been a continuation of the data obtained by the same methods prior to said meeting and have been submitted to the entire membership of the board in regular monthly reports.

Dr. O. E. Meinzer, geologist in charge, Division of Ground Water, United States Geological Survey, visited Fort Caswell at the request of the chairman and at various stages in the investigation gave advice based upon his wide experience in ground-water studies. The 500 and 600 trench experiments and one of the methods of obtaining samples from different water levels which produced the most decisive results were planned during his visit.

Division of work.—The general administration and supervision of the work have been conducted by the chairman.

The engineering features of the work have been conducted by Sanitary Engineer H. R. Crohurst.

Unavoidable circumstances made it impossible for more than one bacteriologist, Gordon E. Thomson, to remain permanently with the work, and the rapid turnover of personnel in the grade of laboratory aids resulted in frequent changes in this element of personnel.

Dr. Norah Dowell Stearns, geologist in the Geological Survey, was assigned to the investigation for one month by Doctor Meinzer to make a geologic and hydrologic study of the Fort Caswell experimental field.

Two of the laboratory attendants, Thomas L. Petrie and William Jones, trained especially for this work in the beginning of the Fort Caswell experiments, were able to stay with it until the end, but the rapid turnover in the other persons thus graded did not interfere materially with the studies, as their duties were of a less exacting nature.

Acknowledgments.—It is with pleasure that the chairman acknowledges the cooperation in various ways of the following persons not directly connected with the board:

Surg. Gen. M. W. Ireland, United States Army, through whose interest in the experiments the board was able to obtain permission of the War Department to conduct the work at Fort Caswell.

Capt. H. B. Bliss, United States Army, commanding officer of Fort Caswell during the early part of the experiment.

Capt. G. W. Dunn, jr., United States Army, stationed at Fort Caswell during the early part of the experiment.

Lieut. H. H. Newman, United States Army, commanding officer of Fort Caswell during a later period of the experiment.

Surg. George W. McCoy, director United States Hygienic Laboratory.

Dr. J. A. Dosher, United States Public Health Service, Cape Fear Quarantine Station.

Mr. J. Berg, United States Public Health Service, Cape Fear Quarantine Station.

2. GENERAL DISCUSSION AND SUMMARY OF RESULTS

By C. W. Stiles

Statement of problem.—*How far will excretal pollution of soil travel?*—In connection with the problem of extension of excretal pollution, either from storage in pits or in subsequent disposal methods, two seemingly distinct but in reality intergrading problems are obvious, namely:

a (*b*) *surface pollution* by surface drainage (or wash); and

b (*a*) *subsurface pollution* by subsurface drainage (wash or flow).

With full realization of the fact that *surface pollution* grades imperceptibly into *subsurface pollution*, the present discussion deals more especially with the *subsurface* factors.

In connection with the more restricted problem of *subsurface pollution*, two seemingly distinct but in reality intergrading problems are obvious, namely,

c (*d*) drainage (of seepage or wash) from the bottom of a pit or from a stratum of soil in which the excreta are buried *down* to the ground-water table; and

d (*c*) drainage or flow in the ground water.

In extreme cases, where the ground water is far below the excretal deposit stratum, these two problems (*c* and *d*) are quite distinct; but in cases of opposite extreme, when the ground water is so high that it enters or surrounds the excretal deposit stratum, as, for example, in cases where the pit pierces the ground-water table, the two problems *c* and *d* merge into one, namely, *d*.

The present report deals with both *c* (pp. 14–121) and *d* (pp. 122–134), but more in detail with *d;* and since *d* is the larger of the two problems, this (pp. 14–121) will be discussed first.

The problem *d* (namely, subsurface drainage or flow of excretal pollution in the ground water) is to be divided further into two distinct problems, namely, e (*f*) *chemical*[1] *pollution* (pollution by dissolved or suspended nonliving materials present in the excreta); and

f (*e*) *biological*[2] (*chiefly bacterial*) *pollution* (pollution by bacteria and other living objects contained in the excreta).

Both *chemical* (*e*) and *biological* (*f*) pollutions are considered in the present report.

e (*f*) To illustrate the possibilities of chemical pollution we have used a dye (uranin) experimentally.

f (*e*) In biological pollution the chief objects which come into consideration are bacteria, parasitic protozoa, and parasitic worms.

The protozoa and worms, parasitic in man or other animals, do not as a rule reproduce outside of the hosts. Accordingly, in studying their possible spread in the ground water, the mathematical probability of finding these animals in cyst, egg, embryo, larva, or adult stage, any considerable distance from the point of pollution, is so infinitesimally small that they do not lend themselves readily as criteria for distant pollution, and as the problems of artificial cultures to increase the numbers of these organisms are so expensive, difficult, or even impossible, both protozoa and worms are to be abandoned as important criteria in studies of this nature.

The fecal bacteria, however, are not only vastly more numerous as respects individuals of a given species, but when not specifically determinable directly in an original sample they can be so increased in number by culture methods as to make specific determination a *practical* procedure. Accordingly, from the practical point of view, it is the bacteria in excreta rather than the animals in excreta which are available as criteria as to extension of biological excretal pollution.

Very naturally, certain excreta bacteria come into special consideration, namely, the bacteria of the tuberculoses, of the typhoids, of the dysenteries, and *Bacillus coli*[3] (i. e., *Escherichia*). Whatever may be the opinion in regard to the greater value of a demonstration on basis of tuberculosis, typhoid, or dysentery, as compared with one based upon *B. coli*, practical considerations dictate the use of *B. coli* as criterion in the studies; not only are the mathematical chances greater for finding *B. coli*, but the expense involved in searching for the others would have been prohibitive.

---

[1] The word *chemical* is not altogether satisfactory in this case. *Inanimate* might be better in some respects, but while one of its meanings is *lifeless* (the underlying thought in *e*), it might be interpreted as excluding the *dead* though once living. The term "chemical pollution" is more or less current at present It is used here in a very broad sense to include everything which is not actually and demonstrably alive; materials which are soluble are the more important; dead plant tissues and dead animal tissues should also be included in the concept.

[2] The word *biological* is not altogether satisfactory, for it includes dead tissues. *Viable* would be still less satisfactory. The distinction to be drawn between *e* and *f* is that the *organisms* (animal or plant) in *f* are still alive when encountered; the objects included in *e* are not alive, though some of them may once have been alive.

From a practical point of view, the question is: Are the objects theoretically capable of reproduction (*f*) when found, or are they theoretically incapable of reproduction when found (*e*)?

The current terms *chemical* and *biological* are used here with full appreciation of the fact that neither is entirely satisfactory.

Accordingly, "fecal *B. coli*" has been accepted as criterion for the presence of fecal pollution; and this in harmony with present world-wide standards.

If the reader desires to raise the point that a demonstration based upon *B. coli* is of lesser value than a demonstration based on tuberculosis, typhoid, or dysentery, his position will not be challenged by the present authors. Our reply, however, is that—

1. Chemical pollution from excreta is not, from our point of view, an asset to wells.

2. The ground water in the present experiments was moving slowly, only a few inches per day.

3. Given a viability (in soil and feces) of the typhoid bacilli from 30 to 90 days (up to 5½ months is generally accepted on basis of one published observation), and a ground water moving from 10 to 100 even to 400 feet per day, it is difficult to establish a distance to which typhoid would not travel; while the viability increases at lower temperatures, the rate of ground-water flow and evaporation also (hence upward capillarity) increase at higher temperatures.

4. *B. coli* pollution is at present a rather generally accepted international standard of nonpotableness of water—a question not under discussion in this report.

EXTENSION OF EXCRETAL POLLUTION IN THE GROUND WATER

Condensed conclusions.—In the conditions surrounding these experiments (sandy soil, slowly moving ground water, free from *B. coli*, all-the-year-round experiment), *bacterial* pollution (*Bacillus coli*) has been recovered from the ground water (well water) in 1,213 samples, taken under a most rigid technique, at distances varying from 1 to 232 feet away from the experimental trench into which the uranin+excreta pollution was placed; *chemical* pollution (uranin) was recovered from the ground water (well water) from the experimental wells up to 450 feet from the same trench; both uranin and *B. coli* traveled in only one direction, namely, in the direction of the ground-water flow; neither uranin nor *B. coli* was found in other portions of the experimental field; wet weather

---

[3] The taxonomic restrictions to which *Bacillus coli* (Escherich, 1886) has been subjected from time to time are the natural result of advance of knowledge.

Bacillus coli, as used in this report, corresponds to *Escherichia* Castellani & Chalmers, 1920, AIP, Sept., p. 619, tod. *E. coli* (Escherich, 1886 [Bacterium]) Cast. & Chalm., 1920, p. 619. (This is dated 1918 by Cast. & Chalm., but we have not been able to confirm this date.) This is distinguished from *Aerobacter* Beijerinck, 1900, CfB, Mar. 31, p. 198, tod. *A. aerogenes* (Escherich, 1886 [Bacillus]) Beijerinck, 1900, p. 200. See Bergey's (1923) Manual of Determinative Bacteriology, p. 194.

Bergey's Manual (pp. 194–205) cites 22 species of *Escherichia*. As shown by our technique (p. 135), our determination runs *Bacillus coli* by Standard Methods (1923) down to *Escherichia* but does not run the species down. Thus *B. coli* of the present report is *B. coli* (*sensu lato*), but of the genus *Escherichia*.

(resulting in high ground water) is conducive to extension of pollution; dry weather (resulting in low ground water) is inhibitive of the extension of pollution and conducive to purification of the ground water; *B. coli* tends to localize in the upper blanket at or near the ground-water table, and water samples in a given well, from this blanket, may show heavy *B. coli* pollution, while water samples a few inches lower may be *B. coli* negative; when the ground water falls, *B. coli* tends to filter out into the capillary *fringe* or (in case of further fall) into the soil; if the soil remains dry sufficiently long, *B. coli* dies; uranin appears to float out in a blanket at or parallel and close to the ground-water table, and tends to filter out (upon fall of ground water) into the capillary *fringe* and soil, but does not seem always to rise with higher ground water.

Experimental *B. coli* infection of the ground water had remained alive for two years eight months when last examined (June 18, 1925). Uranin remained visible in the ground water for two years seven months when last examined (June 5, 1925).

The changes of the ground-water elevations appear to be very complex and of at least four kinds. Without challenging (1) the upward trend of the ground-water table more or less generally attributed to hydraulic pressure from some point upstream (not demonstrated in our studies), or (2) the superposition of new ground water by transit from surface water (as rain) downward to an old ground-water table (not studied in our experiments), indications are not lacking that there may be (3) a new (higher) ground-water table (p. 25, 107) due to a flow of new water from upstream over a former ground-water table, and (4) a wave flow (p. 118) from upstream over a former ground-water table. These movements seem to play an important rôle in the progression of the pollution, carrying the bacteria along to more distant points.

As pollution travels it does not appear to expand laterally (in a fan-shape) with the trench as the apex of a section of a truncate cone, but, on the contrary, it appears to contract to narrower breadth, with the trench representing the base of a truncated section of a cone. For instance, in one experiment the blanket was 25 feet broad at the trench and at a distance of 329 feet in the direction of ground-water flow it had contracted to about 3½ feet in breadth. Due to a change of conditions at about this distance (ocean tide, current, waves), it broadened out distally again and measured 21 feet broad at 450 feet from the trench.

As the maximum probable breadth of pollution (assuming ideal conditions) from a circular pit or cesspool is equal to the diameter of the pit (say, 3 feet), whatever may be the direction of the ground-water flow; and as the maximum probable breadth of the pollution (assuming ideal conditions) from a square pit (say, 3 by 3 feet) varies from the length of one side (say, 3 feet) to the hypotenuse (say, 4.24 feet) according to the direction of ground-water flow, it is obvious that circular pits have a mathematical advantage (as respects safety) over square or oblong pits.

Given a point of pollution (privy, manure pile, etc.) as the center of a circle with a radius of x feet, it is obvious that a greater number of wells can be placed on the circumference if the radius is $3x$ than $2x$ and $2x$ than $1x$, etc.; accordingly, the greater the distance of a well from a point of pollution, the less likely it is to become polluted from said pollution, because (*a*) as the band of pollution extends toward the periphery of the circle, it strikes the circle as the chord (represented by its breadth), say, 3 feet of an arc, and the greater the diameter of the circle the greater the number of 3-foot chords; and (*b*) the longer the radius the greater the chances are for the band of pollution to contract in breadth (say, less than 3 feet). Accordingly, if the direction of flow of ground water is unknown, *distance* represents the great factor in safety.

Ground-water pollution experiments were conducted at Fort Caswell, N. C., from October 4, 1921, to June 22, 1925. The field was located between the beach (Atlantic Ocean on the south) and Elizabeth River (on the north), in a sand area (p. 15), with relatively little vegetation in the experimental field (p. 137).

There were eight sets of wells. Groups 100, 200, and 300 represented control wells, about 50 in number. Groups 500A, 500B, 600A, 600B, and 900 represented the ground water pollution plots, with a total of about 500 permanent and temporary wells.

The ground water for the entire area was found to be normally negative for *B. coli* by an examination of 6,409 water samples taken from a large number of wells and classified (p. 17) as Controls A (1,717 samples), B (1,645 samples), and C (3,047 samples).

Experimental pollution (April 24, 1921, to May 31, 1923) resulted in 1,170 *B. coli* positive samples in Groups 500A, 500B, 600A, 600B, and 900.

Group 600B (Exhibit 21 and p. 51) represents the most convincing experiment and will be taken as the principal example to show results.

A trench 25 feet long (parallel to the ocean), 1.5 feet wide, and 0.6 foot deep was dug into the (momentarily very high) ground-water table. This trench was dosed with human excreta plus uranin. Parallel to the trench, lines of sterilized pipe wells (p. 51) were placed. From October 13, 1922, to May 31, 1923, 1,313 water samples were examined from a total of 122 wells arranged in 21 parallel lines spaced 2 to 115 feet south of the trench.

Uranin and *B. coli* moved out gradually at or very close to the ground-water table, and both were recovered in water samples taken from wells 2 feet to 65 feet south of the trench; uranin was recovered from wells as far as 115 feet south of the trench.

Of the total 1,313 water samples taken 2 to 115 feet from the trench, 417 samples (32 per cent) were *B. coli* positive; of the 1,221 samples taken 2 to 65 feet south of the trench, 417 samples (34 per cent) were *B. coli* positive.

(*a*) As 6,409 (A, B, and C) control samples taken from the general experimental field were *B. coli* negative (p. 17); (*b*) as 34 per cent of the 1,221 samples taken 2 to 65 feet south of the trench were *B. coli* positive; as these (*b*) *B. coli* positive samples corresponded not only with the restricted plot which the uranin showed to be contaminated from the trench; and as the area beyond 65 feet out to 115 feet was still *B. coli* negative; the conclusion is drawn that the *B. coli* contamination found 2 to 65 feet south of the trench came from the contaminated trench—the nearest source of known contamination.

In later surveys (after restriction of work) the following further results were obtained:

Governmental financial considerations made it imperative to reduce personnel, and hence restrict work in June, 1923. Accordingly, after May 31, 1923, only occasional surveys of the field could be made, based upon a reduced number of water samples. As a result, the further progress of uranin and *B. coli* pollution could not be followed step by step; but, fortunately, it has been possible to establish its distribution at various long intervals; in this further progress (subsequent to May 31, 1923) it is important to recall that up to May 31, 1923, 92 water samples, from 22 wells spaced at intervals from 70 to 115 feet south of the trench and in the direction of the ground-water flow from the trench were *B. coli* negative, although this plot had become uranin positive.

In Group 600B experiment (p. 63) uranin pollution was eventually recovered from wells up to a distance of 450 feet south of the trench in the direction of the ground-water flow; *B. coli* was eventually recovered up to 228 (232 diagonally) feet south of the trench.

Group 500B (Exhibit 17 and p. 40) represents the second best of the five demonstrations of the uranin and *B. coli* contamination. In this experiment conditions were complicated by the fact that underlying the upper sand layer there was a layer of peat-like material which curved upward toward the surface about 50 feet south of the trench. As the pollution moved out it was evidently obstructed by this up-curve which upon high ground water would result in an underground waterfall.

Briefly summarized, the trench was first polluted September 25, 1922, with uranin + human excreta; in all there were 26 dosings with excreta, or with uranin + excreta, from September 25, 1922, to October 23, 1923. Uranin and *B. coli* pollution was traced up to 70 feet south of the trench.

Of 2,001 water samples taken from 111 wells (September 25, 1922, to May 10, 1923), arranged in lines from 3 to 50 feet south of the trench, 666 samples (33 per cent) were *B. coli* positive, in the same restricted plot which became uranin positive.

It is interesting to note the rather close agreement of *B. coli* positives in Group 600B (32 per cent, 2 to 65 feet) and Group 500B (33 per cent, 3 to 50 feet).

Group 500A had brought out an exceedingly important point which was not demonstrated early in the other experiments and which gave the clew to further studies.

In a total of 452 water samples, taken from a total of 46 wells, spaced in 14 lines (1 north, 13 south of and parallel to the trench), *B. coli* was recovered in 14 samples (3 per cent). All of these *B. coli* positive samples were taken 1 to 3½ feet south of the trench, while 45 samples from 6 wells north of the trench were *B. coli* negative.

Unable to understand why the uranin and *B. coli* contamination did not progress beyond 3½ feet, we dug up part of the area and subjected part to boring for soil samples; in addition, various temporary wells were put in. This procedure resulted in proving that the ground-water table had fallen and that uranin had filtered out in a band in the capillary fringe and it was possible to trace uranin as far as 23 feet south of the trench, while it was eventually traced in well water out as far as 45 feet; and *B. coli* was also found in the capillary fringe out as far as 12 feet.

The conclusion seems obvious: When the ground-water table fell both uranin and *B. coli* remained in the new capillary fringe to such an extent that they were not recovered in samples taken from the wells which were drawing water from a lower depth; as the water table rose, as an effect of rainfall, the stranded pollution was obviously caught by the elevated water table and carried further away from the trench. Alternating high and low ground water, with corresponding position of the pollution at one time at the water table, at another time in the capillary fringe, is in harmony both chronologically and physically with the findings as respects the extension of the pollution and presents a satisfactory explanation of the data obtained.

In Group 900 (p. 76), an attempt was made to force uranin and *B. coli* pollution some distance below the water table, but the mechanical difficulties encountered were so extreme that the experiment was abandoned. Not until too late to test the subject further did another technique seem to show some promise of results. Despite the negative results of the experiment, from the viewpoint of its original object, uranin and *B. coli* were recovered from well water on the downstream side of the pollution, uranin to a distance of 13¾ feet, and *B. coli* to a distance of 6 feet.

In connection with these experiments it became necessary to devise special pipe wells (see p. 119). These permitted the adoption of an extreme, academic technique, which has stood the inspection of several well-known bacteriologists.

In the Fort Caswell experiments the pollution was placed into the ground-water table. The proof of how the ground water can become polluted from a trench or pit the floor of which is above the ground water is given in the experiments (p. 122) conducted at the United States Marine Hospital in Wilmington, N. C., about 25 miles removed from the Fort Caswell experimental field.

In one of the these Wilmington experiments pollution (excreta + uranin) was placed in a pit, the floor of which was located 3 feet above the water table; and both uranin and *B. coli* were recovered (p. 131) from an experimental well 6 feet away which had been tested for weeks and found to be pollution negative. Other pits were polluted with excreta (without uranin), storm and flood conditions were experimentally produced (p. 126), and *B. coli* was recovered (p. 127) in the sand at various levels (6 to 60 inches) under the floor of the pit and in the ground water; as the sand layers dried they became (175 days after pollution) *B. coli* negative. Still other pits were polluted (with excreta but not with uranin) and *B. coli* was recovered from the underlying sand and from the near-by (up to 60 inches laterally) capillary fringe.

Thus the complete proof is given that—

(1) The sand strata, the capillary fringe, and the ground water immediately below a pit became polluted from the pit (Wilmington experiments) both (*a*) under storm and flood conditions and (*b*) under nonstorm and nonflood conditions; and

(2) Pollution in the ground water was recovered (Fort Caswell experiments) up to 232 feet (*B. coli*) and 450 feet (uranin) away from and on the "downstream" (as respects ground-water flow) side of the pollution.

The distance to which pollution can extend depends upon various factors (p. 88), including rate of ground-water flow (say, 1 inch to 400 feet per day), the pH of the soil, the geological formation, bacterial competition, available food supply, bacterial mortality, rise and fall of ground water dependent upon the weather, etc.

The pollution floats out into the upper blanket of the ground water, close to the table; if the table lowers, the pollution tends to filter out (by capillarity and filtration) into the capillary fringe, and as the capillary fringe assumes a lower position the pollution tends to filter out into the dry sand. As wet weather returns, the water table rises and the surviving pollution is carried further up and out. If the dry weather lasts long enough, the bacteria die.

Thus we find *a law of nature* (p. 28) that *the alternation of dry and wet weather, dependent in the last analysis upon the amount of rainfall, is a potent (possibly the most potent) factor in the purification of drinking (well) water, and were it not for this alternating play in the forces of nature a pure drinking (well) water above an impervious layer would be rare or nonexistent.*

The foregoing data prove that the most dangerous well is that which is located in the direct path of the down-hill flow of the ground water from the point of pollution. Other radii of the circle, with the point of pollution as center, become increasingly safer (p. 95) until the radii on the upstream side of the pollution are reached, and these latter radii are (so far as present knowledge is available) entirely safe, except in so far as the ground-water flow may be reversed into the cone produced by heavy pumping (p. 95).

As the pollution in the ground water is concentrated chiefly between the level of highest ground water and a level a short distance (in our experience less than 1 foot) below lowest ground water, the conclusion would appear justified that this band is the chief underground danger zone of the wells (under conditions of sand, etc., represented in the experiments) and that a leak in a well pipe in this zone is of special danger.

According to generally adopted standards, the bacterial dilution for *B. coli* (+ in 0.1, + in 1.0, + in 10.0 cc.) is given an important weight in considering whether the water is potable or nonpotable. Our studies would seem to indicate that the value of this dilution may be overestimated, for a rise in ground water, following a rain, is likely to change a low-count (high-dilution) well into a high-count (low-dilution) well in a few hours' time.

A band of pollution tends to become narrower (p. 51) as it progresses away from the point of pollution; accordingly, distance (p. 93) is one of the greatest factors of safety.

A circular pit is mathematically safer (p. 97) than either a square or an oblong pit.

The final practical conclusions are that the deep burial of excreta is more dangerous than burial high above the ground-water table, and that while the nonwater-tight pit is a tremendous improvement over promiscuous soil pollution, it is less safe than a water-tight pit, and its safety or danger varies with the direction and rate of ground-water flow. If the direction of the ground-water flow is not known, the safety of the pit is more or less a matter of chance, but if uranin is placed in the pit at time of its construction or installation this chemical will *probably* reach a given well before bacterial pollution reaches it.

Although the burial of dead bodies was not studied in these experiments, the same general principles would apply, namely, whatever danger be assumed to obtain in burial of dead human or animal bodies, the closer the body is placed to the ground water the greater the chances of spread of pollution from it by the ground water. I have personally opened a number of human graves in which the remains were actually in the ground water.

The report closes with a discussion by Doctor Stearns on the geological data of the Fort Caswell experimental field (p. 137).

Attempts were made to repeat elsewhere in gravel soil the Fort Caswell experiments (made in sandy soil).

In Maryland, in a field underlaid with gravel and with high ground water, preliminary tests showed the ground-water table to be so contaminated with *B. coli* as to render experimental pollution of little or no value.

At Fort Hunt, Va., in a field with clay underlaid with gravel and (about) 20 to 25 feet to the ground-water table, it took five persons one-half a day to accomplish (in sinking a well) what one person could accomplish in five minutes or less in the Fort Caswell sand. Even then the clay prevented the up-and-down movement of the well pipe deemed desirable for satisfactory experimental work. Accordingly, the expenses connected with the work promised to be prohibitive.

In another field in Virginia, with underlying gravel and high ground-water table, preliminary examination of the water table showed such heavy *B. coli* contamination that experimental pollution was considered of no real scientific value as a working premise.

Although the work was then abandoned, the point was of decided interest that in the two gravel fields with high ground water the water table was contaminated with *B. coli*—probably from cattle pastured in these two fields.

As a final point of considerable practical as well as theoretical interest the fact is to be mentioned that one of our large experimental pipe wells at the United States Marine Hospital Reservation in Wilmington, N. C., frequently showed *B. coli* contamination, which at the time could not be definitely or even satisfactorily explained. After the point was established at Fort Caswell that *B. coli* tends to locate at or near the top of the water table and (on falling ground water) to filter out into the capillary fringe, the question arose as to whether this pipe were not cracked in the danger zone between high and low ground water. With this working hypothesis in mind, an excavation was made surrounding the well and *a crack in the pipe was actually located in the zone in question.* Our interpretation is that contamination had occurred as the water table rose to the level of this crack. This instance is very suggestive as one of the explanations of *B. coli* contamination of incased wells, and, in view of the oxygen-tropism (see p. 90) of *B. coli*, we are inclined to leave the question *sub judice* whether contamination of deep origin actually occurs in the case of *deep* pipe wells—pending proof that this type of contamination is actually demonstrated.

3. EXPERIMENTAL[1] SPREAD OF POLLUTION IN GROUND WATER IN SAND AT FORT CASWELL, N. C.

By C. W. Stiles, H. R. Crohurst, and G. E. Thomson

Collaborators F. Wales, A. J. Speer, G. Brown, M. E. Felt, H. E. Alexander, and E. Dunn

Introduction.—The two points at issue in this chapter are the questions: *Given the fact that pollution gains access to ground water* (as from a pit or cesspool), (*a*) *Can the pollution spread, and* if so, (*b*) *in what direction?* Related questions, as, for instance, regarding the principles influencing the spread, pro or con, will be discussed in another chapter (see p. 88).

Classification of water samples into controls, etc.—The total 8,269 water samples under immediate consideration can be classified into five natural groups, each differing from the other four by some one distinct environmental character, as follows:

Samples A = Controls A.—Of the total 8,269 water samples, 1,717 were taken from October 4, 1921, to April 23, 1922, a period of about six and one-half months, prior to the introduction (April 24, 1922) of experimental *Bacillus coli* pollution on to any portion of any plot of the entire experimental field. Accordingly, these 1,717 samples represent theoretical academically absolute controls for the dates in question. *B. coli* was not found in any sample of Controls A.

Samples B = Controls B.—Of the 8,269 samples, 1,645 were taken after April 23, 1922, i. e., beginning April 24, 1922 (the first day of introduction of experimental *B. coli* pollution on to any portion of any plot of the entire experimental field) and ending May 31, 1923, but under the following conditions:

536 samples from wells of Group 100, the plot of which received no experimental *B. coli* pollution at any time.

444 samples from wells of Group 200, ditto.

665 samples from wells of Group 300, the plot of which received experimental *B. coli* pollution at one point (in a pit at the center) under conditions which seem theoretically to exclude contamination of the wells from this experimental pollution.

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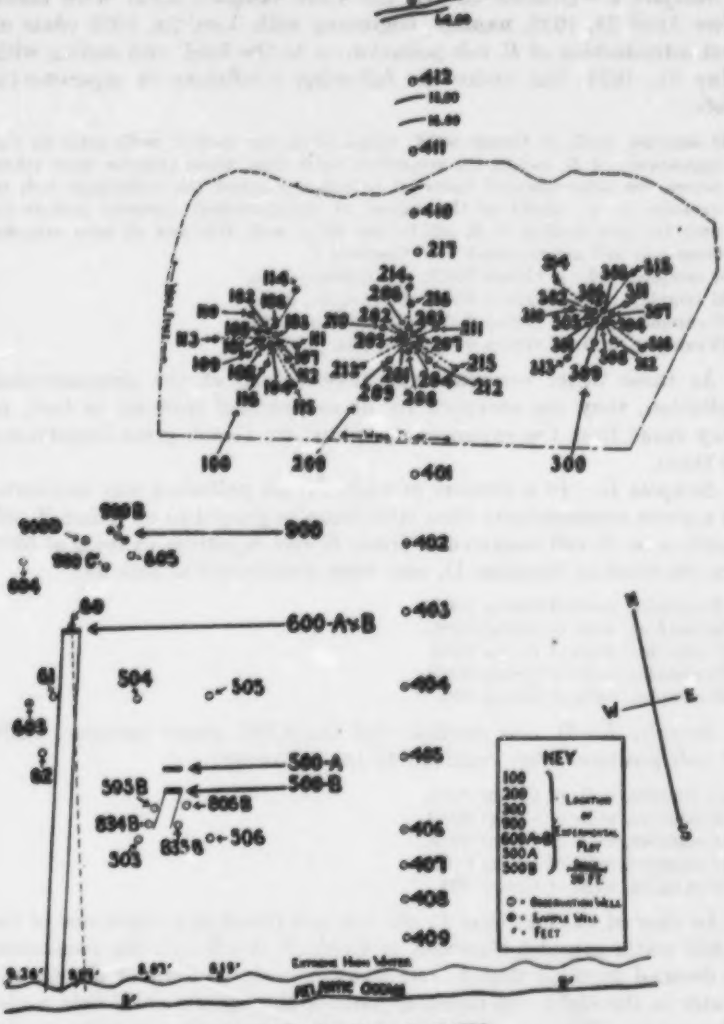
[1] *Division of work.*—The experiments were planned and supervised by Stiles and Crohurst; the engineering work was performed by Crohurst; the 8,269 bacteriological determinations were made by Thomson and collaborators; the tabulations were made by Thomson; the argument, interpretation, and conclusions were prepared by Stiles and are concurred in by Crohurst and Thomson. Prior to these Fort Caswell experiments similar trench and pit experiments were conducted on the United States Marine Hospital Reservation in Wilmington, N. C., but in only one of these was uranin used; *B. coli* was recovered at various distances, up to about 120 feet, away from experimental trenches; in the distant pollutions, however, the bacterial results were not paralleled by uranin results. The Fort Caswell experiments were originally undertaken to determine whether the Wilmington results could be confirmed; the uranin control—used in only one Wilmington pit—was given greater emphasis in the Fort Caswell experiments. As the later (Fort Caswell) studies are more convincing than the earlier (Wilmington), it appears unnecessary to publish the Wilmington details.

EXHIBIT 1.—*Diagram of experimental field, showing location of plots*



412
411
410
217
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403
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405
406
407
408
409
100
200
300
900
900B
900 C
605
604
60
600-A&B
61
603
62
504
505
500-A
500-B
505B
834B
303
833B
806B
306
KEY
100
200
300
900
600A&B
500A
500B
Location of Experimental Plot
Scale 50 Ft.
○ = Observation Well
● = Sample Well
' = Feet
N
S
E
W
Extreme High Water
ATLANTIC OCEAN
Elev. 0.00 Low Water Aug. 31, 1922

Accordingly, these 1,645 samples represent theoretical academically absolute controls for the dates in question. *B. coli* was not found in any sample of Controls B.

Samples C = Controls C.—Of the 8,269 samples, 3,047 were taken after April 23, 1922, namely, beginning with April 24, 1922 (date of first introduction of *B. coli* pollution on to the field) and ending with May 31, 1923, but under the following conditions *in experimental plots:*

432 samples, wells of Group 500A, taken from the various wells prior to the appearance of *B. coli* in the respective well; thus, these samples were taken before the demonstrated bacterial pollution reached the individual well in question (i. e., ahead of the spread of demonstrated bacterial pollution); with the first finding of *B. coli* in any given well, this and all later samples from said well are excluded from Controls C.
951 samples, wells of Group 500B; ditto; ditto; ditto.
586 samples, wells of Group 600A; ditto; ditto; ditto.
650 samples, wells of Group 600B; ditto; ditto; ditto.
428 samples, wells of Group 900; ditto; ditto; ditto.

As these water samples were taken *ahead* of the demonstrated pollution, they are accepted by us as *practical controls;* in fact, as they come from the experimental plots, we attach great importance to them.

Samples D.—In a number of wells *B. coli* pollution was recovered at a given examination; then later samples proved to be either *B. coli* positive or *B. coli* negative. These *B. coli* negatives (a total of 690) are classified as Samples D, and were distributed as follows:

6 samples, wells of Group 500A.
384 samples, wells of Group 500B.
21 samples, wells of Group 600A.
246 samples, wells of Group 600B.
33 samples, wells of Group 900.

Samples E = B. coli *positive.*—Of the 8,269 water samples, 1,170 *B. coli* positives were confined to the following:

14 samples, wells of Group 500A.
666 samples, wells of Group 500B.
54 samples, wells of Group 600A.
417 samples, wells of Group 600B.
19 samples, wells of Group 900.

In view of the fact that *B. coli* was not found in a single one of the 6,409 water samples classified as Controls A + B + C, the conclusion is deemed justified that *B. coli* was not an inhabitant of the ground water in the eight experimental plots of the experimental field under discussion. When a given set of wells shows pollution with uranin, the conclusion is drawn that this uranin was the experimental uranin placed into the experimental excreta, and when both uranin and *B. coli* are recovered from a given set of wells, the conclusion is drawn that the *B. coli* also represent the experimental *B. coli*.

A summary of the classification of water Samples A to E, with total, is seen in Exhibit 2.

EXHIBIT 2.—*Tabular summary of 8,269 water samples, October 4, 1921, to May 31, 1923*

Group	B. coli negative							B. coli positive (Samples E)	Grand total, A–E
	Controls A	Controls B	Controls C	Samples D	A+B	A+B+C	A+B+C+D		
100	495	536	None.	None.	1,031	1,031	1,031	None.	1,031
200	603	444	None.	None.	1,047	1,047	1,047	None.	1,047
300	603	665	None.	None.	1,268	1,268	1,268	None.	1,268
500A	16	None.	432	6	16	448	454	14	468
500B	None.	None.	951	384	None.	951	1,335	666	2,001
600A	None.	None.	586	21	None.	586	607	54	661
600B	None.	None.	650	246	None.	650	896	417	1,313
900	None.	None.	428	33	None.	428	461	19	480
Totals:									
100 to 300	1,701	1,645	None.	None.	3,346	3,346	3,346	None.	3,346
500A to 600B	16	None.	2,619	657	16	2,635	3,292	1,151	4,443
100 to 900	1,717	1,645	3,047	690	3,362	6,409	7,099	1,170	8,269
Dates	Oct. 4, 1921, to Apr. 23, 1922	Apr. 24, 1922, to May 31, 1923			Oct. 4, 1921, to May 31, 1923				

(*a*) As pollution with uranin and with *B. coli* was totally absent from Group 100, Group 200, and Group 300;

(*b*) As pollution with uranin and with *B. coli* was found only in Group 500A, Group 500B, Group 600A, Group 600B, and Group 900;

It is in order to establish the detailed findings for the various groups and wells in question.

GROUP 200—CONTROLS A AND B

(Bacteriological determinations by Thomson, Wales, Brown, and Dunn)

This group of 16 wells, Nos. 201 to 216, furnished 603 Controls A and 444 Controls B; total, 1,047 Controls A and B.

Of the total 1,047 samples, 674 showed gas, *but not one of these gas samples confirmed as Bacillus coli.* Of the 603 Controls A, 463 samples (=76.78 per cent) showed gas, and of the 444 Controls B, 211 samples (=47.52 per cent) showed gas.

Accordingly, the Control Group 200 is entirely negative for *B. coli.* This fact alone would suggest that in connection with any *B. coli* water sample from any other group the thought would lie near that this contamination might be connected in some way with our experimental pollution.

Since, however, 463 (=ca. 77 per cent) of the Controls A and 211 (=ca. 48 per cent) of the Controls B in the absolute control set (Group 200) of wells showed gas (which, however, did not confirm as due to *B. coli*), it seems wise to eliminate gas production *per se* as a proof of extension of the fecal pollution; and since the gas production (77 per cent) was higher in the Controls A than (48 per cent) in the Controls B, it would be difficult to assume that the gas production in the Controls B bore any relation to the introduction of pollution into the experimental field laterally or downstream from Group 200. From this point on gas production will be referred to only as a matter of record routine and not as part of the essential argument.[2]

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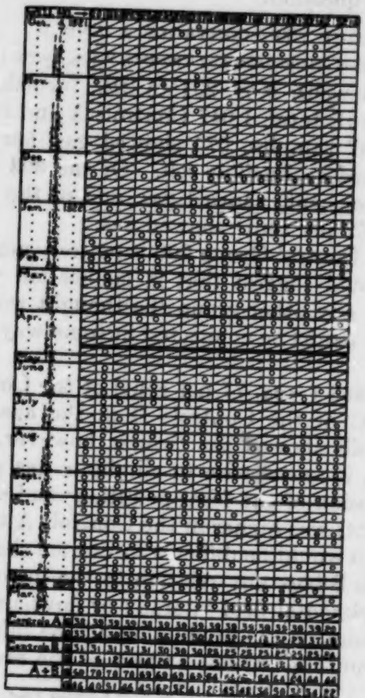
[2] Mr. R. E. Noble cultured out 238 water samples (95 from polluted wells and 143 from normal wells) and 33 sand samples (from various well sites and from various spots in the experimental field) which showed *presumptive B. coli* (i. e., gas formation in lactose) and proved the presence of anaerobic spore formers.

The details for the separate wells are as follows (Exhibits 2 and 3):

EXHIBIT 3.—*Controls A and B, Group 200, arranged by wells*

Well No.	A: Oct. 4, 1921–Apr. 22, 1922			B: Apr. 24, 1922–May 31, 1923		
	Number of samples	Gas		Number of samples	Gas	
		Absent	Present		Absent	Present
201	38	5	33	31	18	13
202	39	5	34	31	25	6
203	39	0	39	31	19	12
204	39	7	32	31	17	14
205	38	7	31	31	17	14
206	39	3	36	30	4	26
207	39	16	23	30	21	9
208	39	9	30	30	19	11
209	39	18	21	25	20	5
210	39	7	32	25	12	13
211	39	12	27	25	4	21
212	39	21	18	25	9	16
213	39	7	32	25	7	18
214	39	16	23	25	16	9
215	39	2	37	25	8	17
216	20	5	15	24	17	7
Total, 16 wells	603	140	463	444	233	211
Per cent			77			48

EXHIBIT 4.—*Diagram showing log of 16 wells of Group 200, Controls A and B*



Key:— ☐ No sample; ⊡ No gas; ▨ Gas:

GROUP 300—CONTROLS A AND B

(Bacteriological determinations by Thomson, Weiss, Speer, and Dunn)

This group of 16 wells, Nos. 301 to 316, furnished 603 Controls A, 665 Controls B; total, 1,268.

Of the total 1,268 samples, October 4, 1921, to May 31, 1923, 883 (=69.64 per cent) showed gas, but in no case did the gas-producing samples show *Bacillus coli*. Of the 603 Controls A, 450 (=74.63 per cent) showed gas, and of the 665 Controls B, 433 (=65.11 per cent) showed gas.

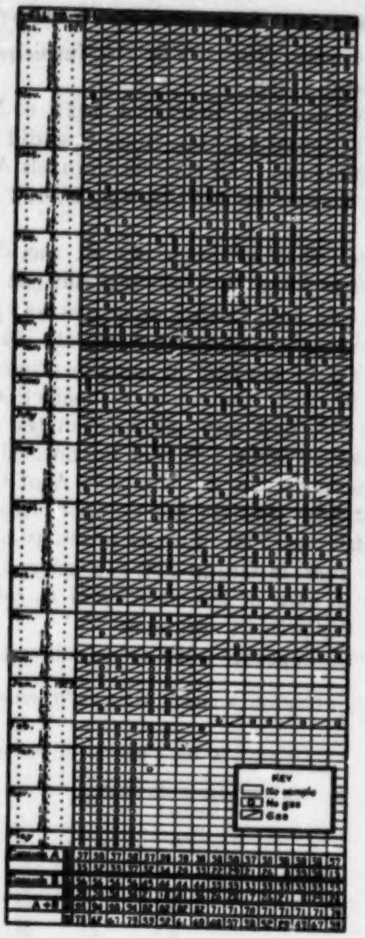
It is to be noted that although the pit was dosed with human excreta, commencing May 15, 1922, this did not result in infecting the wells with *B. coli*, and, further, since gas was produced in 75 per cent of the samples taken prior to April 24, 1922, while a smaller percentage, namely, 65 per cent of samples produced gas from April 24, 1922, to May 31, 1923, there is no evidence that the dosing which began May 15, 1922, had any influence in the gas production by samples from these 16 wells. It will be noticed also that the gas production (75 per cent) in the Controls A of Group 300 was not radically different from that (77 per cent) of Group 200, but that in the Controls B of Group 300, the gas production (65 per cent) was materially higher than in Group 200 (48 per cent); this is an interesting point, but in view of the absence of *B. coli* no importance is attached to it in the present argument.

The details for the separate wells are as follows (Exhibits 5 and 6):

EXHIBIT 5.—*Controls A and B, Group 300, arranged by wells*

Well No.	A: Oct. 4, 1921–Apr. 23, 1922			B: Apr. 24, 1922–May 31, 1923		
	Number of samples	Gas		Number of samples	Gas	
		Absent	Present		Absent	Present
301	37	2	35	56	18	38
302	38	6	32	56	26	30
303	37	4	33	56	22	34
304	38	1	37	56	20	36
305	37	5	32	45	24	21
306	38	4	34	44	26	18
307	38	18	20	44	3	41
308	38	5	33	44	8	36
309	38	16	22	33	7	26
310	38	9	29	33	5	28
311	37	16	21	33	16	17
312	38	12	26	33	7	26
313	38	30	8	33	12	21
314	38	3	35	33	25	8
315	38	0	38	33	4	29
316	37	22	15	33	9	24
Total, 16 wells	603	153	450	665	232	433
Per cent			75			65

Exhibit 6.—*Diagram showing log of 16 wells of Group 300, Controls A and B*



GROUP 100—CONTROLS A AND B

(Bacteriological determinations by Thomson)

This group of 16 wells, Nos. 101 to 116, furnished 495 Controls A and 536 Controls B; total, 1,031.

Of the total 1,031 samples, 491 (=47.62 per cent) showed gas, but in no case was *B. coli* found.

Of the 495 Controls A, 350 (=70.71 per cent) showed gas, and of the 536 Controls B, 141 (=26.31 per cent) showed gas.

It will be noted that the gas (71 per cent) in the Controls A is not radically different from that in Group 200 (77 per cent) and Group

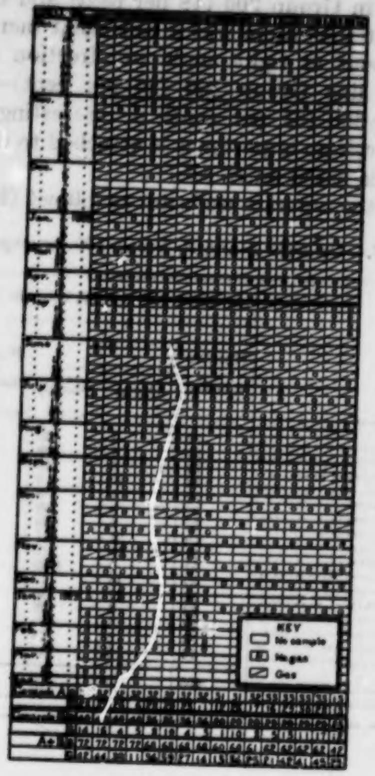
300 (75 per cent), but that in the Controls B the gas (26 per cent) is much lower than in Group 200 (48 per cent) and in Group 300 (65 per cent); the fact that there was a consistent increase in gas from west to east (about at right angle to direction of ground-water flow) along the line Group 100 (26 per cent)—Group 200 (48 per cent)—Group 300 (65 per cent) is interesting, but in view of the absence of *B. coli* no importance is attached to this in the present argument, which is based on *B. coli*.

The details for the separate wells are as follows (Exhibits 7 and 8):

Exhibit 7.—*Controls A and B, Group 100, arranged by wells*

Well No.	A: Oct. 4, 1921–Apr. 23, 1922			B: Apr. 24, 1922–May 31 1923		
	Number of samples	Gas		Number of samples	Gas	
		Absent	Present		Absent	Present
101	29	4	25	40	26	14
102	32	4	28	40	24	16
103	32	6	26	40	36	4
104	32	26	6	40	35	5
105	32	4	28	36	28	8
106	32	3	29	36	26	10
107	32	9	23	36	32	4
108	32	21	11	36	33	3
109	22	10	12	29	28	1
110	31	6	25	29	19	10
111	32	15	17	29	21	8
112	33	17	16	29	24	5
113	33	4	29	29	16	13
114	33	3	30	29	18	11
115	33	5	28	29	12	17
116	18	0	18	30	17	13
Total, 16 wells	495	145	350	536	395	141
Per cent			71			26

EXHIBIT 8.—*Diagram showing log of 16 wells of Group 100, Controls A and B*



GROUP 500 A—CONTROLS A, B, AND C; SAMPLES D AND E

(Bacteriological determinations by Thomson)

This group contained 46 wells, Nos. 501 to 578.

A trench was dug, 25 feet long, running east to west, 2 feet wide, and about 3 feet deep into the top of the ground water; wells were placed in lines parallel to this trench, as shown in Exhibit 9. The trench was dosed on April 24 and 25, 1922, with cow dung (diluted with water) and with uranin.

In all, 468 water samples were examined; of these, 422 were gas negative, 46 gas positive, 14 *B. coli* positive. These samples were distributed as follows:

Prior to (April 24) dosing: 16 samples (from 9 wells) on the 1-foot line south of (downstream from) the trench; of these, 13 were gas negative, 3 (=18.75 per cent) gas positive, 16 *B. coli* negative, 0 *B. coli* positive. These are Controls A.

After the (April 24) dosing up to and including September 18, 1922, there were 452 water samples taken; of these, 409 were gas negative, 43 gas positive, 438 *B. coli* negative, 14 *B. coli* positive.

The 438 *B. coli* negative samples can be classified into two categories, namely:

C.—There were 432 taken from wells before the well in question showed any instance of *B. coli* infection; in other words, they were taken ahead of the extension of demonstrated pollution; while these 432 samples are not *Academic* controls in the sense of Controls A and B, they are *Practical* controls in the sense of Controls C.

D.—The 6 remaining *B. coli* negative samples were taken from wells after these wells had shown *B. coli* positive, but had apparently become, at least temporarily, *B. coli* negative; these 6 samples are classified as Samples D.

Exhibit 9a.—*Chart 500A plot, showing trench, location of wells, soil excavations, and extension of uranin and B. coli*

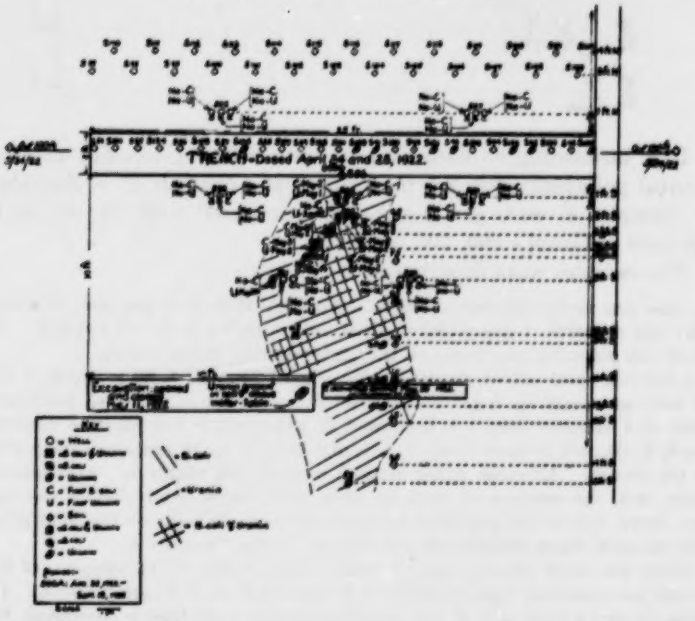
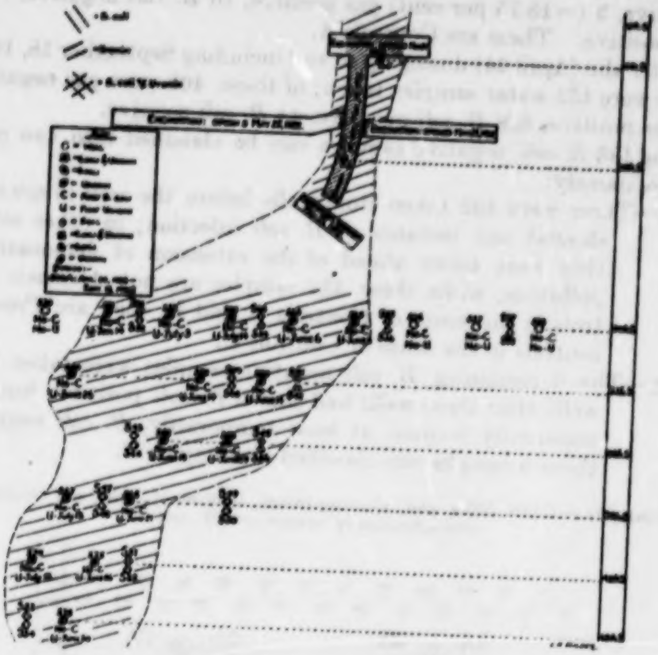


Exhibit 9b.—*Chart 500A plot, showing trench, location of wells, soil excavations, and extension of uranin and B. coli*



It is interesting to note that in spite of the proximity to experimental pollution, only 9.5 per cent of the *Controls C* + Samples D + Samples E were gas positive, as compared with 26, 48, and 65 per cent of Groups 100, 200, and 300.

The samples were distributed as follows:

1-foot line north (upstream), 6 wells.—April 25–May 5, 45 samples; of these, 44 were gas negative, 1 gas positive, 45 *B. coli* negative, 0 *B. coli* positive. Thus no *B. coli* pollution was found on the upstream side of the trench.

1-foot line south (downstream), 9 wells.—April 24–May 5, 89 samples; of these, 85 were gas negative, 4 gas positive, 85 *B. coli* negative, 4 *B. coli* positive. A total of 4 samples from 1 well showed *B. coli* positive four days in succession, the 8, 9, 10, and 11 days (May 2, 3, 4, and 5) of (i. e., *of*, not *after*) the pollution of the trench. All other water samples were *B. coli* negative. As a matter of exact fact, the samples of April 24 were taken immediately before the trench was dosed, but as the pollution had actually been brought on the field prior to this moment, these samples are not included in the Controls A.

2-foot line south (downstream), 3 wells.—May 2–May 5, 12 samples; of these, 4 were gas negative, 8 gas positive, 4 *B. coli* negative, 8 *B. coli* positive. Three wells showed a total of 8 *B. coli* positive samples, four days in succession, 9, 10, 11, and 12 days (May 2, 3, 4, and 5) of pollution. All other water samples were *B. coli* negative.

2¾-foot line south (downstream), 1 well.—May 3–May 29, 10 water samples; of these, 9 were gas negative, 1 gas positive, 9 *B. coli* negative, 1 *B. coli* positive. The *B. coli* sample was the thirty-fourth (May 29) day *of* pollution (i. e., 33 days *after* pollution).

3½-foot line south (downstream), 1 well.—May 3–5, 3 samples; 2 gas negative, 1 gas positive, 2 *B. coli* negative, 1 *B. coli* positive. This *B. coli* sample was taken on the thirty-sixth day *of* (i. e., thirty-fifth day *after*) pollution. This is the farthest point from the trench that *B. coli* was found in any water sample of this series.

3¾-foot line south (downstream), 1 well.—May 3–5, 3 samples; 3 gas negative, 0 gas positive, 3 *B. coli* negative, 0 *B. coli* positive.

Negative *B. coli* water (290) samples on more distant (5 to 45 feet) downstream lines were as follows:

5-foot line south, 6 wells.—April 2–May 5, 33 samples, all gas negative.

30-foot line south, 9 wells.—June 9–September 18, 106 samples, of which 94 were gas negative, 12 gas positive.

33-foot line south, 3 wells.—June 14–September 13, 54 samples, of which 50 were gas negative, 4 gas positive.

36-foot line south, 2 wells.—June 20–September 13, 35 samples, of which 32 were gas negative, 3 gas positive.

39-foot line south, 2 wells.—June 21–September 13, 31 samples, of which 26 were gas negative, 5 gas positive.

42-foot line south, 2 wells.—June 26–September 13, 17 samples, of which 16 were gas negative, 1 gas positive.

45-foot line south, 1 well.—June 30–September 13, 14 samples, of which 11 were gas negative, 3 gas positive. Uranin was recovered from this well June 30 and this represents the farthest point at which water samples were uranin positive.

In view of the fact that uranin was found in the lines (1, 2, 2¾, and 3½ feet south) in which *B. coli* (14 samples) was found, the uncontrovertible proof is given that material from the trench was recovered in the wells; and in view of the proximity to experimental pollution and the absence of *B. coli* from all the Controls A and B and the absence of *B. coli* from such a large number of other samples (Controls C), it would be difficult to argue that the *B. coli* pollution in question came from some source other than the trench.

This difficulty becomes increased when it is considered that 7 samples from well No. 502a were *B. coli* negative (April 22, 23, 25, 26, 27, and 28, and May 1) immediately prior to the four days (May 2, 3, 4, and 5) when this well showed *B. coli* positive.

The conclusion is submitted that the *B. coli* contamination, in common with the uranin contamination, came from the trench.

That *B. coli* could not be recovered in wells beyond well 502i (3½ feet from the trench) was at first not understood. Data having a possible bearing on this fact were:

April 24.—All water samples uranin negative.
April 25.—Approximate *elevation* of ground-water table under pit, 8.80 feet
April 25, 26, 27, 28.—All water samples uranin negative.
April 29.—*Rainfall, 1.12 inches.*

May 1.—Approximate *elevation* of ground-water table under pit, 9.08 feet.

Uranin first appeared in Well 502a (1 foot south), i. e., *after a rain resulting in the rise of the water table.*

May 2.—Uranin recovered from 6 wells, i. e., 1 at (502a) 1 foot south and 5 (500e, f, g, h, and i) 2 feet south.

B. coli recovered in 4 wells, i. e., 1 (502a) 1 foot south and 3 (500e, f, and g) 2 feet south, *after a rise* (May 1) *in the ground-water table.*

May 3.—Uranin present in 6 wells (502a, e, f, h, g, and i), not found in 20 others. *B. coli* appeared in 1 additional well (502i) 3½ feet south.

May 4.—Rainfall 0.28 inches. Uranin appeared in 2 new (temporary) wells (502l, 1 foot; and 502k, 3 feet south of the trench).

May 5.—Uranin in wells 502a, e, f, g, h, and i; not found in 27 other wells.

May 7.—Uranin in wells 502a, e, h, and i; not found in 32 other wells.

May 8.—Uranin in wells 502a, e, h, and i.

May 9.—Uranin in wells 502a, e, h, and i.

May 10.—Approximate elevation of ground water under pit, 8.72 feet.

Accordingly, there has been no discoverable spread of either uranin or B. coli *for some days and during this period the ground-water table had fallen.*

May 11.—In order to trace what had become of the uranin, a trench was dug starting 10 feet south of the west end of the pollution trench and extending 10 feet nearly parallel to the pollution trench. *Uranin was discovered in this new trench, not at the water table but in the capillary fringe about 9 inches above the water table. Thus uranin had passed outward (south) at least 10 feet and had become stranded as the ground water fell.* This became a clew for further work.

May 12.—No new uranin.

May 13.—Uranin recovered (by soil boring) from capillary fringe at points 6 feet from trench (2½ feet below ground surface), 10 feet (2½ to 3 feet below), 12 feet (2½ feet below); soil samples uranin negative at 2, 4, 8, and 14 feet south; water samples uranin negative at 10 feet south; *B. coli* positive soil samples at 6 feet, 10 and 12 feet south; *B. coli* negative at 4 and 12 feet south. *Thus both* B. coli *and uranin had extended 12 feet south and had filtered out into the capillary fringe as the water table fell.*

May 14.—Rainfall, 0.34 inch. Up to this date uranin had been recovered in wells (permanent or temporary) out to 4 feet south; uranin in the soil 6 to 12 feet out.

May 15.—Approximate elevation of water table under the trench, 8.60 feet.

Uranin in a temporary well (502bb) 32 inches from trench, 7½ feet below ground level. Uranin found in soil 15 and 17 feet south of trench, but these samples were *B. coli* negative.

May 16.—Rain began 7.30 p. m.

May 17.—Rain ended 10 a. m. *Rainfall, 2.12 inches.* Water table under trench rose to approximately 9.50 feet in elevation. Uranin present in wells 502e, h, and i; *also in a temporary well 10 feet south* and 17 feet south; also in soil 4½ feet from the trench. Due to rain, the ground water has now risen approximately to within 2½ feet below ground surface; as the uranin in the soil (prior to rain) was 2½ feet below ground surface, it is now at the water table. Prediction is that uranin will now appear in wells farther out.

May 18.—Rainfall, 0.19 inch. Water table elevation under trench, 9.50 feet.

Uranin recovered in wells at 10 and 17 feet (512a).

May 19.—Uranin in Wells 502e, h, and i; also in a temporary well 10 feet south; well at 17 feet south uranin negative.

May 20.—Rainfall, 0.17 inch. Uranin in wells 502a, bb, e, f, h, and i; also in temporary well 10 feet south of the trench.

May 22.—Uranin in wells 502a, bb, e, h, and i; also in 2 other wells, 1 at 10 feet south and 1 at 17 feet south; 1 well 10 feet south uranin negative. A soil sample (17 feet south) 1 foot from uranin positive well (17 feet south) strongly uranin positive at or just above water table. Soil sample 20 feet south uranin negative.

May 23.—Uranin present in wells 502a, e, h, and i; also in 1 well 10 feet south and 1 well 17 feet south.

May 24.—Twelve soil samples at different levels, 20 to 100 feet outside of the 500 and 600 groups, *B. coli* negative. One sample was taken from the surface of the ground immediately under a patch of dried out cow dung. A new trench opened in midline of 500A slightly less than 17 feet out to 23 feet south of trench. Uranin band (about 6 inches broad) traced in soil along entire new trench. Uranin present in wells 502a, e, and h, and temporary wells 10 and 17 feet south.

May 25.—Uranin in wells 502a, e, and i, and temporary wells at 10 and 17 feet south.

May 26.—Rainfall, 0.66 inch.

May 27.—Uranin in wells 502a and h; also in temporary wells 10 and 17 feet south.

May 29.—Rainfall, 1.65 inches. Uranin in wells 502a, e, h, and i; 511a (first appearance); also in two temporary wells 10 and 17 feet, respectively, south. Water table in four observation wells average 9.68 feet in elevation (503 at 8.69, 504 at 10.42, 505 at 10.52, and 506 at 9.08 feet).

May 30.—Rainfall, 0.08 inch. Water table under trench, about 9.60 feet in elevation. Average elevation of four observation wells, 9.60 (503 at 8.56, 504 at 10.42, 505 at 10.43, and 506 at 8.99 feet).

June 6.—Line of 8 wells (Nos. 531 to 538) placed parallel to trench on line 30 feet south, bottom of wells 2 to 2½ feet below ground level and practically at water table. Elevation of water table: Under trench, 9.90 feet; average elevation of four observation wells 9.65 (503 at 8.73, 504 at 10.74, 505 at 10.[illegible]3, and 506 at 9.28 feet). *With this high ground water*, well 534 showed uranin positive. Prediction that uranin will now spread.

June 8.—Uranin present in wells 534 and 535.

June 9.—Uranin present in wells 534 and 535. Elevations of water table: Under trench, 9.64 feet; average of four observation wells, 9.64 (503 at 8.49, 504 at 10.49, 505 at 10.60, and 506 at 9 feet).

June 10.—Uranin in wells 534 and 535.

June 12.—Uranin in 502b, e, f, g, h, and 534; also in two temporary wells at 10 and 17 feet south, respectively.

June 14.—Uranin in wells 531, 533, and 534 on the 30-foot line south; also in new wells 552 and 553 on the 33-foot line south. *Thus, on high ground water uranin has extended.*

June 15.—Uranin same as June 14.

June 16.—Uranin same as of June 14 and 15. Elevations of water table: At trench, 9.19 feet; average of four observation wells, 9.19 (503 at 8.04, 504 at 10.05, 505 at 10.13, and 506 at 8.55 feet).

June 17.—Uranin same as of June 14, 15, and 16.

June 18.—Rainfall, p. m. 18th to a. m. 19th, 0.70 inch.

June 19.—Uranin same as June 14, 15, 16, and 17; and in addition, *on high ground water*, it has spread to well 562 on the 36-foot line south. Water-table elevation, 9.20 feet at trench.

June 20.—Uranin same as June 19. Water-table elevation, a. m., June 20: 10.42 at pit; average for four observation wells, 10.12 (9.12 at 503, 11.36 at 504, 11.59 at 505, and 9.59 at 506) feet. *Rainfall June 19, p. m., to June 20, a. m., 3.95 inches.* Prediction that uranin will spread. Water-table elevations, p. m., June 20: 10.35 at trench; average for four observation wells, 10.35 (9.13 at 503, 11.20 at 504, 11.51 at 505, and 9.57 at 506) feet.

June 21.—Uranin in wells 531 and 533 at 30 feet south; in 552 at 33 feet south; has spread to 562 at 36 feet and 568 at 39 feet south, respectively. Water-table elevations: 10.22 at trench; average of four observation wells, 10.22 (9.06 at 503, 11.03 at 504, 11.30 at 505, and 9.52 at 506) feet. Night rainfall 21st to a. m. 22d, 0.45 inch. Prediction that uranin will spread.

June 22.—Uranin in wells 531, 533, 534, and 535 at 30 feet; 552 and 553 at 33 feet; 562 at 36 feet, and 568 at 39 feet south, respectively. Water-table elevations: 10.27 at trench; average of four observation wells, 10.27 (9.02 at 503, 11.07 at 504, 11.35 at 505, and 9.60 at 506) feet. Prediction that uranin will spread.

June 23.—Uranin in wells 531, 533, 534, 552, 562, and 568. Water-table elevations: 10.11 at trench; average of four observation wells, 10.12 (8.91 at 503, 10.96 at 504, 11.16 at 505, and 9.44 at 506) feet.

June 24.—Uranin same as June 23. Water-table elevations: 10.02 at trench; average of four observation wells, 10.02 (8.82 at 503, 10.90 at 504, 11.04 at 505, and 9.33 at 506) feet.

June 26.—Uranin in wells 531, 533, 534, and 535 at 30 feet south; 550 and 552 at 33 feet south; 562 at 36 feet south; 568 at 39 feet south; 575 at 42 feet south. Thus expectation that uranin would spread has been realized. Night rainfall 0.05 inch.

June 27.—Uranin in wells 531, 533, and 534 at 30 feet south; 550, 552, and 553 at 33 feet south; 562 at 36 feet south; 568 at 39 feet south; and 575 at 42 feet south. P. m. rainfall, 0.12 inch.

June 28.—Water-table elevations: 9.76 at trench; average of four observation wells, 9.76 (8.52 at 503, 10.67 at 504, 10.79 at 505, and 9.06 at 506) feet.

June 29.—Uranin in wells 531, 533, 534, 550, 552, 553, 562, 563 (first record), 568, and 575. P. m. rainfall, 0.58 inch. Uranin will spread.

June 30.—Uranin in wells 563, 568; also in 578 on line 45 feet south. Thus uranin has extended to the 45-foot line.

July 1.—Water-table elevations: 9.66 at trench; average of four observation wells, 9.67 (8.47 at 503, 10.56 at 504, 10.69 at 505, and 8.96 at 506) feet.

July 3.—Uranin in wells 531, 532, 533, 550, 552, 562, 568, 575, and 578.

July 4–5.—Rainfall, 2.06 inches.

July 5.—Water-table elevations: 9.52 at trench; 9.52 average of four observation wells (8.17 at 503, 10.48 at 504, 10.65 at 505, and 8.79 at 506) feet.

July 6.—Uranin in wells 531, 532, 533, 534, 550, 552, 562, 568, and 575. Water-table elevations: 10.05 at trench, 10.06 average of four observation wells (8.80 at 503, 10.93 at 504, 11.17 at 505, and 9.33 at 506) feet. Uranin expected to spread.

Obviously, during the period April 24 to July 6, the fact was outstanding that it was at times of high elevation of the water table that the uranin pollution spread, while at times of lower elevation it was more stationary, and at very low elevation it was filtered out into the capillary fringe. The one discoverable variant in the experiment was the weather, with resulting change in water table, and it is to this latter that we attribute stasis and progression of the pollution.

B. coli pollution (12 feet south) did not extend so far as was expected. Possibly this was due to the fact that the excreta in this experiment consisted of cow dung (collected from the pastures and not always too fresh and moist) which had to be mixed with water; the thought suggests itself that possibly the living bacteria were neither so numerous nor so vigorous as were the bacteria in the much fresher human excreta used in Groups 500B and 600B.

In order to obtain data in harmony with, possibly explanatory of, the stasis of the uranin at the 45-foot line, the subsurface was explored, and it was found that the peat layer curved upward in the region of the 45-foot to 50-foot line and thus formed a barrier to the free flow of low ground water; in fact, a sort of underground pond existed here which required an unusually high ground water to create an underground waterfall over the crest of the peat. Even in case of the formation of this waterfall there are indications, in another part of our studies, that the uranin would probably not flow over the crest so rapidly as would *B. coli.*

The data for the separate lines and wells are as follows (Exhibits 10 to 12):

Exhibit 10.—*Summary of Group 500A by lines, Controls A and C, Samples D (B. coli negative) and E (B. coli positive)*

Total by lines	Controls A–Oct. 4, 1921–Apr. 23, 1922					Apr. 24, 1922–Sept. 18, 1922					Controls C	Samples D	B. coli first recovered
	Number of samples	Gas absent	Gas present	B. coli absent	B. coli present	Number of samples	Gas absent	Gas present	B. coli absent	B. coli present (Samples E)			
1 foot north (6 wells)						45	44	1	45	0	45	0	
1 foot south (9 wells)	16	13	3	16	0	89	85	4	85	4	85	0	May 2, 1922
2 feet south (3 wells)						12	4	8	4	8	0	4	Do.
2¾ feet south (1 well)						10	9	1	9	1	9	0	May 29, 1922
3½ feet south (1 well)						3	2	1	2	1	0	2	May 3, 1922
3¾ feet south (1 well)						3	3	0	3	0	3	0	(1)
5 feet south (6 wells)						33	33	0	33	0	33	0	(1)
30 feet south (9 wells)						106	94	12	106	0	106	0	(1)
33 feet south (3 wells)						54	50	4	54	0	54	0	(1)
36 feet south (2 wells)						35	32	3	35	0	35	0	(1)
39 feet south (2 wells)						31	26	5	31	0	31	0	(1)
42 feet south (3 wells)						17	16	1	17	0	17	0	(1)
45 feet south (1 well)						14	11	3	14	0	14	0	(1)
Total, 14 lines (46 wells)	16	13	3	16	0	452	409	43	438	14	432	6	
Per cent			19					9.5			96	1	

[1] No B. coli.

Exhibit 11.—*Summary of Group 500A by wells*

Distance from trench	Well No.	Controls A: Oct. 4, 1931–Apr. 22, 1932					Apr. 24–Sept. 10, 1932					Controls C	Samples D
		Number of samples	Gas		B. coli		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present		Absent	Present	Absent	Present (Samples B)		
1 foot north	506a	----	----	----	----	----	6	6	0	6	0	6	0
	506b	----	----	----	----	----	6	6	0	6	0	6	0
	506c	----	----	----	----	----	6	6	0	6	0	6	0
	507a	----	----	----	----	----	9	9	0	9	0	9	0
	507b	----	----	----	----	----	9	8	1	9	0	9	0
	507c	----	----	----	----	----	9	9	0	9	0	9	0
	Total	0	0	0	0	0	45	44	1	45	0	45	0
½ foot south	503a	2	2	0	2	0	10	10	0	10	0	10	0
	503b	1	1	0	1	0	10	10	0	10	0	10	0
	503c	1	1	0	1	0	10	10	0	10	0	10	0
	502a	2	0	2	2	0	9	5	4	5	4	5	0
	502b	2	2	0	2	0	10	10	0	10	0	10	0
	502c	2	2	0	2	0	10	10	0	10	0	10	0
	501a	2	1	1	2	0	10	10	0	10	0	10	0
	501b	2	2	0	2	0	10	10	0	10	0	10	0
	501c	2	2	0	2	0	10	10	0	10	0	10	0
	Total	16	13	3	16	0	89	85	4	85	4	85	0
2 feet south	502e	----	----	----	----	----	4	0	4	0	4	0	0
	502f	----	----	----	----	----	4	2	2	2	2	0	2
	502g	----	----	----	----	----	4	2	2	2	2	0	2
	Total	0	0	0	0	0	12	4	8	4	8	0	4
2⅝ feet south	502h	----	----	----	----	----	10	9	1	9	1	9	0
3½ feet south	502i	----	----	----	----	----	3	2	1	2	1	0	2
3⅝ feet south	502j	----	----	----	----	----	3	3	0	3	0	3	0
5 feet south	511a	----	----	----	----	----	5	5	0	5	0	5	0
	511b	----	----	----	----	----	5	5	0	5	0	5	0
	511c	----	----	----	----	----	5	5	0	5	0	5	0
	510a	----	----	----	----	----	6	6	0	6	0	6	0
	510b	----	----	----	----	----	6	6	0	6	0	6	0
	510c	----	----	----	----	----	6	6	0	6	0	6	0
	Total	----	----	----	----	----	33	33	0	33	0	33	0
30 feet south	530	----	----	----	----	----	1	1	0	1	0	1	0
	531	----	----	----	----	----	22	21	1	22	0	22	0
	532	----	----	----	----	----	16	16	0	16	0	16	0
	533	----	----	----	----	----	21	16	5	21	0	21	0
	534	----	----	----	----	----	24	21	3	24	0	24	0
	535	----	----	----	----	----	19	17	2	19	0	19	0
	536	----	----	----	----	----	1	0	1	1	0	1	0
	537	----	----	----	----	----	1	1	0	1	0	1	0
	538	----	----	----	----	----	1	1	0	1	0	1	0
	Total	0	0	0	0	0	106	94	12	106	0	106	0
33 feet south	550	----	----	----	----	----	16	14	2	16	0	16	0
	552	----	----	----	----	----	20	19	1	20	0	20	0
	553	----	----	----	----	----	18	17	1	18	0	18	0
	Total	0	0	0	0	0	54	50	4	54	0	54	0
36 feet south	562	----	----	----	----	----	18	16	2	18	0	18	0
	563	----	----	----	----	----	17	16	1	17	0	17	0
	Total	0	0	0	0	0	35	32	3	35	0	35	0
39 feet south	567	----	----	----	----	----	13	10	3	13	0	13	0
	568	----	----	----	----	----	18	16	2	18	0	18	0
	Total	0	0	0	0	0	31	26	5	31	0	31	0
42 feet south	575	----	----	----	----	----	3	3	0	3	0	3	0
	574	----	----	----	----	----	14	13	1	14	0	14	0
	Total	0	0	0	0	0	17	16	1	17	0	17	0
45 feet south	578	----	----	----	----	----	14	11	3	14	0	14	0
	Total, 46 wells, 14 lines	16	13	3	16	0	452	409	43	438	14	452	6

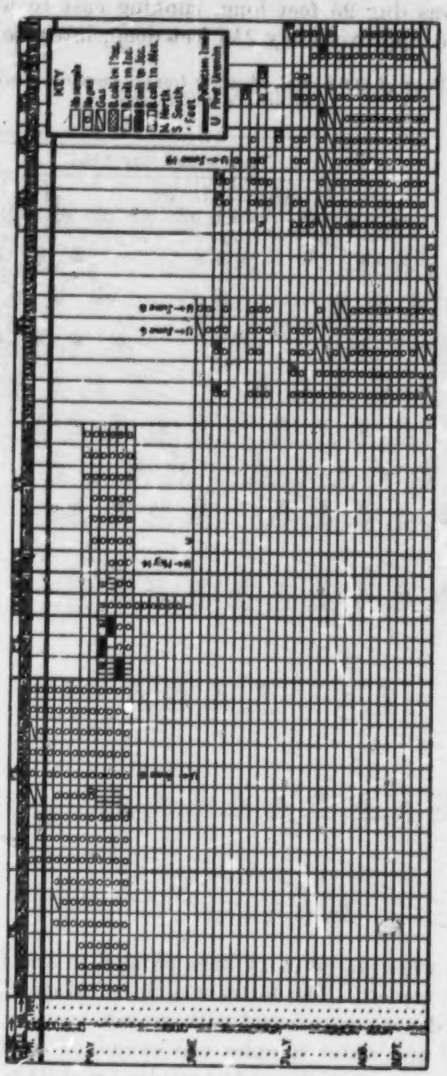


EXHIBIT 12.—*Diagram showing log of 46 wells in 14 lines of Group 500A, October 4, 1921, to September 18, 1922*

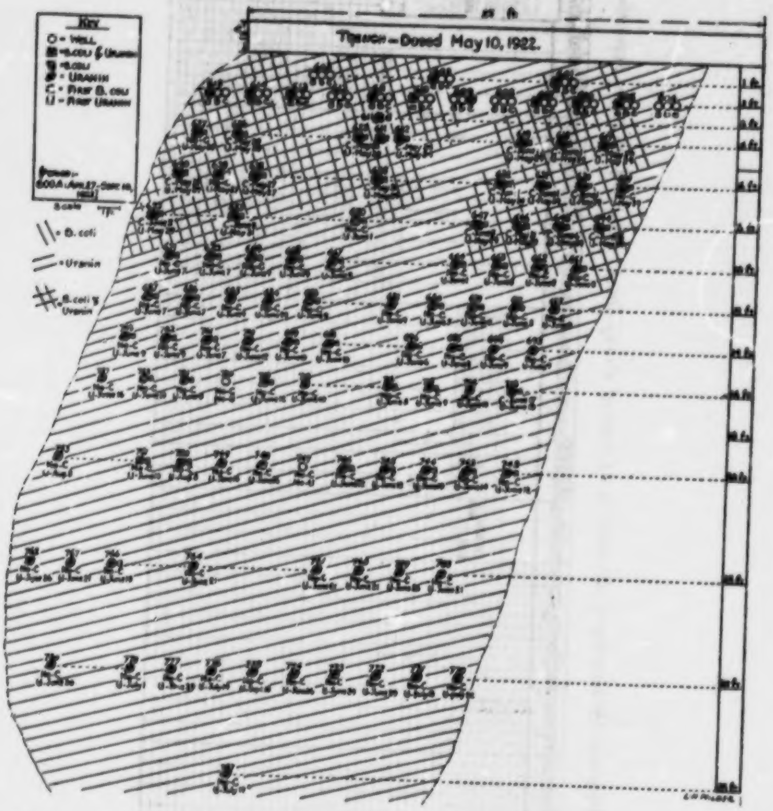
GROUP 600A—CONTROLS C, SAMPLES D AND E

(Bacteriological determinations by Thomson, Speer, and Felt)

This group (Exhibit 13) contained 138 wells, Nos. 603a to 777.

A trench was dug 25 feet long, running east to west, about 1½ feet wide, and approximately 2½ feet deep, into the top of ground water; wells were placed in 14 lines parallel to and from 1 to 35 feet south of the trench. The latter was dosed May 10, 1922, with cow dung (diluted with water) and with uranin.

EXHIBIT 13.—*Chart of 600A plot, showing trench, location of wells, and extension of uranin and B. coli*


Key
○ = Well
▦ = B. coli & Uranin
= B. coli
= Uranin
C = First B. coli
U = First Uranin
Period—
600A Apr. 27–Oct. 1922
Scale
= B. coli
= Uranin
= B. coli & Uranin
25 ft.
Trench—Dosed May 10, 1922.

A total of 661 water samples was examined; of these, 520 (78.66 per cent) were gas negative; 141 samples (=21.33 per cent) were gas positive; 607 were *B. coli* negative; 54 samples (=8.17 per cent) were *B. coli* positive.

Water samples from this group were not examined prior to April 24, 1922, when experimental pollution was first brought upon the experimental field; accordingly, strictly speaking, the 1,701 Controls A of Groups 100, 200, 300, and 500A serve as the controls of Group 600A.

Prior to the introduction (May 10, 1922) of experimental pollution into the plot of the 600A group, there were 53 samples examined for the wells of this group—29 from the 1-foot line and 24 from the 24-foot line. All of these 53 samples were *B. coli* negative. It seems ultraacademic to classify these as Controls C rather than as Controls A, but for the sake of consistency this course will be followed and these 53 controls will be considered with the *B. coli* negative samples (Controls C) of Group 600A (but they are not duplicated in the summary of Exhibit 2).

B. coli positive samples were obtained from the 1, 2, 3, 4, 6, 8, and 16-foot lines; only *B. coli* negative samples were obtained from the 10, 12, 14, 20, 25, 30, and 35-foot lines. The samples are to be classified as follows:

1-foot line south, 9 wells.—Prior to dosing (May 10) the trench all 29 samples from 9 wells were *B. coli* negative; from May 10 to June 28, 2 out of 19 samples were *B. coli* positive. Of the total 48 samples, 42 were gas negative, 6 gas positive; 46 *B. coli* negative, 2 *B. coli* positive.

2-foot line south, 36 wells.—Prior to dosing (May 10) the trench 24 samples from 12 wells were *B. coli* negative; from May 10 to June 15, 18 out of 60 samples were *B. coli* positive. Of the total 84 samples, 61 were gas negative, 23 gas positive, 66 *B. coli* negative, 18 *B. coli* positive.

3-foot line south, 1 well.—May 20 to 23, 3 samples, all *B. coli* positive.

4-foot line south, 8 wells.—May 20 to June 21, 24 samples; of these, 6 were gas negative, 18 gas positive, 12 *B. coli* negative, 12 *B. coli* positive.

6-foot line south, 8 wells.—May 27 to June 21, 32 samples; 17 gas negative, 15 gas positive, 23 *B. coli* negative, 9 *B. coli* positive.

8-foot line south, 7 wells.—May 31 to June 21, 28 samples; 14 gas negative, 14 gas positive, 20 *B. coli* negative, 8 *B. coli* positive.

16-foot line south, 10 wells.—July 9 to August 28, 54 samples; 49 gas negative, 5 gas positive, 52 *B. coli* negative, 2 *B. coli* positive.

For 10, 12, 14, 20, 25, 30, and 35-foot lines, see Exhibit 13.

The chronological order of recovery of *B. coli* at 1 foot (June 12), 2 feet (May 19), 3 and 4 feet (May 20), 8 feet (May 31), 16 feet (June 17), is very suggestive, but will not be advanced as demonstrative; another experiment brings this point out in a more striking way. Naturally when *B. coli* was covered on the 2-foot line the further search for *B. coli* on the 1-foot line was of only secondary interest; in general, as time went on, the samples were taken at greater distances from the trench and the wells nearer the trench presented less argumentative interest.

The statistics for the separate lines and trenches are as follows (Exhibits 14 to 16):

Exhibit 14.—*Summary of Group 600A by Lines, Controls C, Samples D and E*

Total by lines	Apr. 27, 1922-Sept. 18, 1922					Controls C	Samples D	B. coli first recovered
	Number of samples	Gas		B. coli				
		Absent	Present	Absent	Present (Samples E)			
1 foot south (9 wells)	48	42	6	46	2	46	0	June 12
2 feet south (26 wells)	84	61	23	66	18	64	2	May 19
3 feet south (1 well)	3	0	3	0	3	0	0	May 20
4 feet south (8 wells)	24	6	18	12	12	10	2	Do.
6 feet south (8 wells)	32	17	15	23	9	14	9	May 27
8 feet south (7 wells)	28	14	14	20	8	17	3	May 31
10 feet south (9 wells)	83	66	17	83	0	83	0	(1)
12 feet south (10 wells)	91	81	10	91	0	91	0	(1)
14 feet south (10 wells)	77	66	11	77	0	77	0	(1)
16 feet south (10 wells)	54	49	5	52	2	47	5	June 17
20 feet south (11 wells)	47	42	5	47	0	47	0	(1)
25 feet south (8 wells)	42	36	6	42	0	42	0	(1)
30 feet south (10 wells)	46	38	8	46	0	46	0	(1)
35 feet south (1 well)	2	2	0	2	0	2	0	(1)
Total, 14 lines (138 wells)	661	520	141	607	54	586	21	
Per cent			21		8	89	3	

[1] No B. coli.

Exhibit 15.—*Summary of Group 600A by wells, Controls C, Samples D and E*

Distance from trench	Well No	Apr. 27, 1922-Sept. 18, 1922					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
1 foot south	603a	6	4	2	6	0	6	0
	603b	4	4	0	4	0	4	0
	603c	4	4	0	4	0	4	0
	602a	8	6	2	7	1	7	0
	602b	6	6	0	6	0	6	0
	602c	6	6	0	6	0	6	0
	601a	6	4	2	5	1	5	0
	601b	4	4	0	4	0	4	0
	601c	4	4	0	4	0	4	0
Total		48	42	6	46	2	46	0
2 feet south	615a	6	1	5	4	2	3	1
	615b	1	1	0	1	0	1	0
	615c	1	1	0	1	0	1	0
	614a	3	1	2	1	2	1	0
	614b	1	1	0	1	0	1	0
	614c	1	1	0	1	0	1	0
	613a	3	1	2	1	2	1	0
	613b	1	1	0	1	0	1	0
	613c	1	1	0	1	0	1	0
	612a	1	1	0	1	0	1	0
	612b	1	1	0	1	0	1	0
	612c	1	1	0	1	0	1	0
	611a	5	1	4	1	4	1	0
	611b	2	2	0	2	0	2	0
	611c	1	1	0	1	0	1	0
	610a	7	3	4	3	4	3	0
	610b	3	3	0	3	0	3	0
	610c	3	3	0	3	0	3	0
	609a	3	3	0	3	0	3	0
	609b	3	2	0	3	0	3	0

Exhibit 15.—*Summary of Group 600A by wells, Controls C, Samples D and E*—Continued

Distance from trench	Well No.	Apr. 27, 1922–Sept. 18, 1922					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
2 feet south	609c	3	3	0	3	0	3	0
	608a	3	3	0	3	0	3	0
	608b	3	3	0	3	0	3	0
	608c	3	3	0	3	0	3	0
	607a	6	3	3	4	2	3	1
	607b	3	3	0	3	0	3	0
	607c	3	3	0	3	0	3	0
	606a	3	1	2	2	1	3	0
	606b	1	1	0	1	0	1	0
	606c	1	1	0	1	0	1	0
	605a	2	1	1	1	1	1	0
	605b	1	1	0	1	0	1	0
	605c	1	1	0	1	0	1	0
	604a	1	1	0	1	0	1	0
	604b	1	1	0	1	0	1	0
	604c	1	1	0	1	0	1	0
Total		84	61	23	66	18	64	2
3 feet south	611d	3	0	3	0	3	0	0
4 feet south	627a	5	3	2	5	0	5	0
	626a	3	2	1	2	1	1	1
	623a	4	0	4	2	2	2	0
	611e	3	0	3	0	3	0	0
	622a	3	1	2	1	2	0	1
	619a	2	0	2	1	1	1	0
	618a	2	0	2	1	1	1	0
	617a	2	0	2	0	2	0	0
Total		24	6	18	12	12	10	2
6 feet south	640a	6	3	3	4	2	1	3
	639a	7	7	0	7	0	7	0
	638a	3	0	3	1	2	0	1
	635a	7	4	3	6	1	1	5
	632a	1	0	1	0	1	0	0
	631a	1	0	1	0	1	0	0
	630a	2	0	2	0	2	0	0
	629a	5	3	2	5	0	5	0
Total		32	17	15	23	9	14	9
8 feet south	653a	3	2	1	2	1	2	0
	652a	2	0	2	1	1	1	0
	650a	9	8	1	9	0	9	0
	647a	5	1	4	4	1	1	3
	646a	2	0	2	0	2	0	0
	645a	2	0	2	1	1	1	0
	644a	5	3	2	3	2	3	0
Total		28	14	14	20	8	17	3
10 feet south	671a	11	11	0	11	0	11	0
	670a	9	2	7	9	0	9	0
	669a	7	7	0	7	0	7	0
	668a	7	7	0	7	0	7	0
	667a	7	7	0	7	0	7	0
	664a	13	12	1	13	0	13	0
	663a	9	8	1	9	0	9	0
	662a	10	3	7	10	0	10	0
	661a	10	9	1	10	0	10	0
Total		83	66	17	83	0	83	0
12 feet south	687a	11	11	0	11	0	11	0
	686a	10	8	2	10	0	10	0
	685	7	7	0	7	0	7	0
	684	7	7	0	7	0	7	0
	683a	10	10	0	10	0	10	0

Exhibit 15.—*Summary of Group 600A by wells, Controls C, Samples D and E*—Continued

Distance from trench	Well No.	Apr. 27, 1922-Sept. 18, 1922					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (samples E)		
12 feet south Continued)	681	7	7	0	7	0	7	0
	680a	12	12	0	12	0	12	0
	679a	10	10	0	10	0	10	0
	678a	10	8	2	10	0	10	0
	677	7	1	6	7	0	7	0
Total		91	81	10	91	0	91	0
14 feet south	703a	7	6	1	7	0	7	0
	702a	8	8	0	8	0	8	0
	701a	9	9	0	9	0	9	0
	700	6	6	0	6	0	6	0
	699a	8	7	1	8	0	8	0
	698a	9	4	5	9	0	9	0
	696a	10	9	1	10	0	10	0
	695a	8	5	3	8	0	8	0
	694	6	6	0	6	0	6	0
	693	6	5	1	6	0	6	0
Total		77	66	11	77	0	77	0
16 feet south	723	4	4	0	4	0	4	0
	722a	5	4	1	5	0	5	0
	721a	6	6	0	6	0	6	0
	720	1	1	0	1	0	1	0
	719a	6	6	0	6	0	6	0
	718	4	4	0	4	0	4	0
	716a	7	7	0	7	0	7	0
	715a	8	8	0	8	0	8	0
	714	5	4	1	5	0	5	0
	713a	8	5	3	6	2	1	5
Total		54	49	5	52	2	47	5
20 feet south	752	3	3	0	3	0	3	0
	751a	5	5	0	5	0	5	0
	750	1	1	0	1	0	1	0
	749a	7	4	3	7	0	7	0
	748	5	5	0	5	0	5	0
	747	1	1	0	1	0	1	0
	746a	5	5	0	5	0	5	0
	745a	5	5	0	5	0	5	0
	744a	6	6	0	6	0	6	0
	743a	4	4	0	4	0	4	0
	742a	5	3	2	5	0	5	0
Total		47	42	5	47	0	47	0
25 feet south	768	5	4	1	5	0	5	0
	767	5	4	1	5	0	5	0
	766a	6	6	0	6	0	6	0
	764	5	5	0	5	0	5	0
	761	5	2	3	5	0	5	0
	760	5	5	0	5	0	5	0
	759	6	5	1	6	0	6	0
	758	5	5	0	5	0	5	0
Total		42	36	6	42	0	42	0
30 feet south	780	5	5	0	5	0	5	0
	778	6	6	0	6	0	6	0
	777	6	4	2	6	0	6	0
	776	5	5	0	5	0	5	0
	775	1	0	1	1	0	1	0
	774	6	6	0	6	0	6	0
	773	6	6	0	6	0	6	0
	772	6	5	1	6	0	6	0
	771	4	0	4	4	0	4	0
	770	1	1	0	1	0	1	0
Total		46	38	8	46	0	46	0
35 feet south	787	2	2	0	2	0	2	0
Total, 128 wells, 14 lines		661	530	141	607	54	586	21

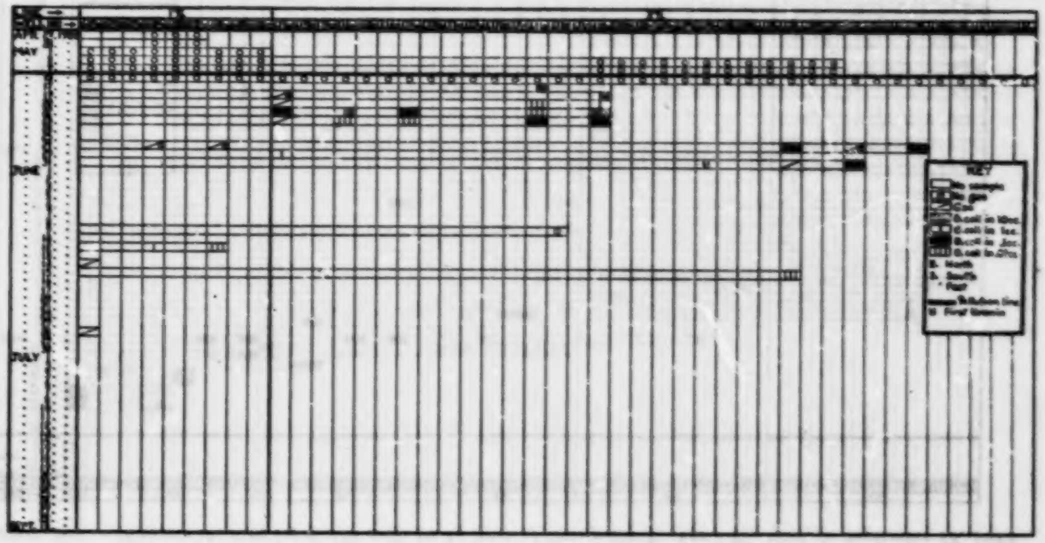
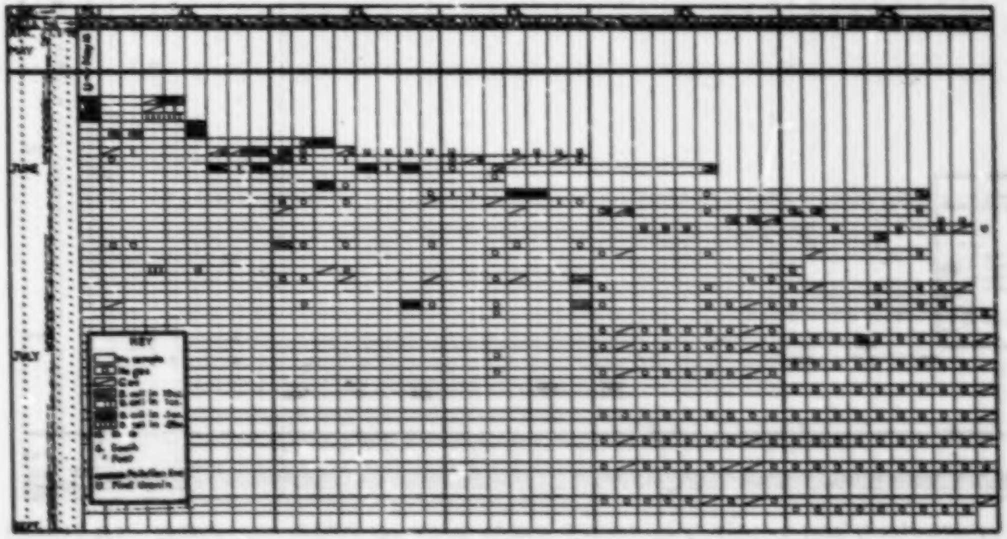


EXHIBIT 16A.—*Diagram showing log of 138 wells in 14 lines of Group 600A, April 27, 1922, to September 18, 1922*

EXHIBIT 16B.—*Diagram showing log of 138 wells in 14 lines of Group 600A, April 27, 1922, to September 18, 1922*



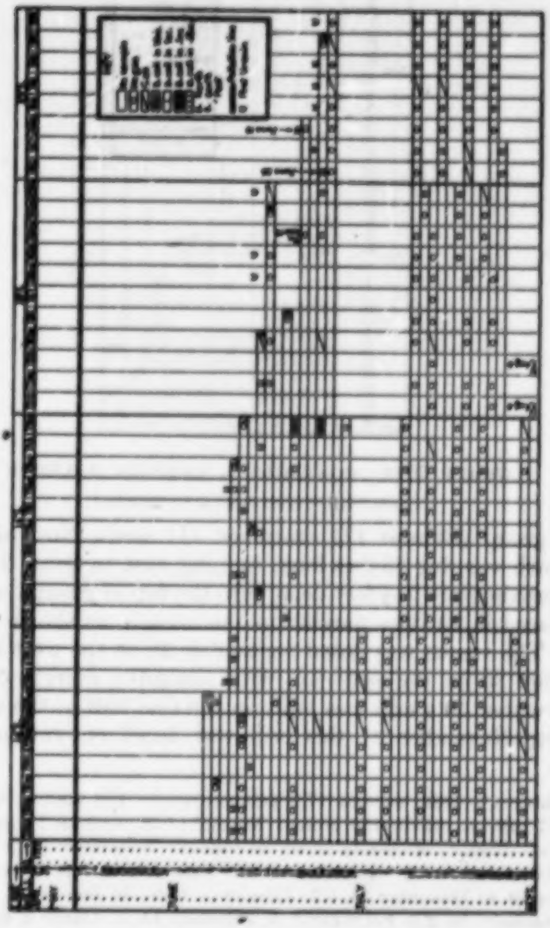
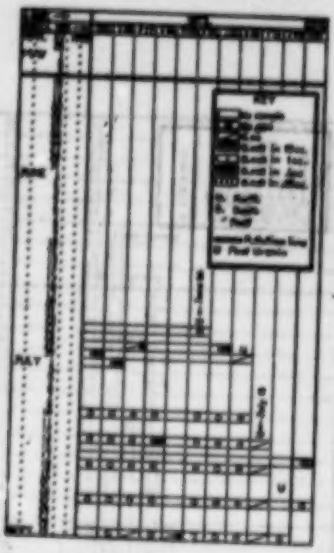


EXHIBIT 16c.—*Diagram showing log of 138 wells in 14 lines of Group 800A, April 27, 1922, to September 18, 1922*

Exhibit 16d.—*Diagram showing log of 138 wells in 14 lines of Group 500A, April 27, 1922, to September 18, 1922*



GROUP 500B—CONTROLS C, SAMPLES D AND E

(Bacteriological determinations by Thomson)

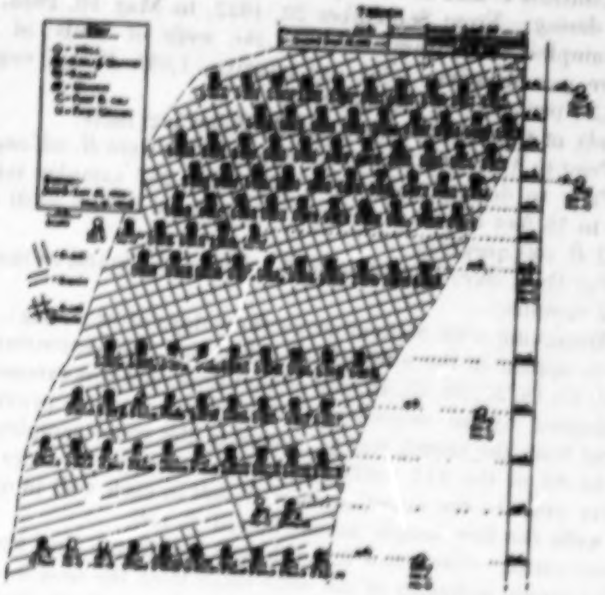
This group (Exhibit 17) contained 111 wells, Nos. 529 to 835a. A trench was dug 25 feet long, running east to west, 2 feet wide, and approximately 2½ feet deep, into the top of ground water; wells were placed in 12 lines parallel to this trench, as shown in the diagram. The trench was dosed September 25 on the west half and on September 30 on the east end, with can-privy excreta plus uranin. On November 20 a crib was built on the east half of the trench, and beginning November 21 this crib was dosed on various dates as follows:

September 25, 1922, excreta 17.9 gallons, uranin 150 grams; September 30, excreta 17 gallons, uranin 150 grams; November 21, excreta 11 gallons, uranin 165 grams. Gallons of excreta added as follows: November 23, 3.9; November 28, 5.3; December 1, 5.5; December 4, 4.3; December 8, 7.1; December 13, 4.2; December 19, 6; December 26, 6.7; January 3, 1923, 5; January 4, 2.3; January 16, 3.5; January 18, 2.2; February 1, 5; February 14, 5; March 2, 6; March 8, 4; April 2, 8; April 3, 8.5 plus a small quantity of uranin; April 26, 5. Total, 22 dosings, excreta 143.4 gallons, uranin 465 grams plus.

September 7, 8.5; September 21, 19.12; October 8, 21.3; October 23, 12.73. Grand total, 26 dosings.

The flow of ground water, as shown by uranin, was somewhat diagonal from northeasterly to southwesterly direction through the trench toward the ocean.

EXHIBIT 17.—*Chart of 500B plot, showing trench, location of wells, and extension of uranin and B. coli*



Controls A.—The same 16 Controls A (prior to April 23, 1922) reported, page 29 for 500A serve as Controls A for 500B.

Controls C.—Prior to the construction of this trench and crib the proximal lines of wells had been used in the 500A experiment; the lines of 500A corresponded to the lines of 500B as follows:

500A—30-foot line....equaled....500B—3-foot line:
33-foot line....equaled.... 6-foot line
36-foot line....equaled.... 9-foot line
39-foot line....equaled....12-foot line
42-foot line....equaled....15-foot line
45-foot line....equaled....18-foot line

Reference to the 500A experiment, page 30, shows 106 samples from 30 feet, 54 samples from 33 feet, 35 samples from 36 feet, 31 samples from 39 feet, 17 samples from 42 feet, and 14 samples from 45 feet, a total of 257 samples from May 5 to September 13, were *B. coli* negative. For all practical purposes these represent controls for the corresponding 3-foot, 6-foot, 9-foot, 12-foot, 15-foot, and 18-foot lines of 500B and show that prior to dosing trench 500B the water samples for the six proximal lines of 500B were *B. coli* negative.

In addition, the 1,335 *B. coli* negative samples can be classified as 951 Controls C and 384 Samples D.

After dosing.—From September 26, 1922, to May 10, 1923, 2,001 water samples were examined from the wells of 500B; of these, 440 were gas negative, 1,561 gas positive, 1,335 *B. coli* negative, 666 (33.28 per cent) *B. coli* positive.

A study of the details brings out the following facts:

(*a*) Prior to April 24, 16 Controls A (see 500A) were *B. coli* negative.

(*b*) Prior to dosing (September 25) 500B, 257 samples taken in lines 3 to 18 feet downstream from but parallel to the 500B trench were all *B. coli* negative.

(*c*) For three days after dosing *B. coli* was not found in the 3-foot line (27 samples).

(*d*) Beginning with September 29 (four days after dosing), *B. coli* began to appear in the wells of the 3-foot line, then extended to the 6, 9, 12, 15, 18, 21, 30, 35, 40, and 50-foot lines, and this extension was accompanied by an extension of the uranin, which proved that material from the trench was recovered in the water samples.

(*e*) In 86 of the 111 wells there was 1 sample or more *B. coli* negative prior to the appearance of *B. coli* in each well in question; in 25 wells the first sample taken showed *B. coli*.

CONCLUSION.—The proof is considered conclusive that the *B. coli* and the uranin pollution of the wells came from the trench.

The details for the separate lines and wells are shown in Exhibits 18 to 20.

EXHIBIT 18.—*Summary of Group 500B by lines, Controls C, Samples D and E*

Total by lines	Sept. 25, 1922-May 10, 1923					Controls C	Samples D	B. coli first recovered
	Number of samples	Gas		B. coli				
		Absent	Present	Absent	Present (Samples E)			
3 feet south (11 wells)	366	82	284	198	168	68	130	Sept. 29, 1922
6 feet south (9 wells)	118	24	94	46	72	12	34	Oct. 2, 1922
9 feet south (11 wells)	134	22	112	38	96	22	16	Oct. 5, 1922
12 feet south (11 wells)	136	33	103	54	82	46	8	Oct. 9, 1922
15 feet south (10 wells)	66	9	57	27	39	11	16	Oct. 16, 1922
18 feet south (6 wells)	20	4	16	11	9	8	3	Oct. 18, 1922
21 feet south (11 wells)	135	10	125	46	89	24	22	Do.
30 feet south (9 wells)	151	44	107	130	21	91	39	Nov. 1, 1922
35 feet south (10 wells)	176	64	112	130	46	88	42	Oct. 31, 1922
40 feet south (10 wells)	251	40	211	208	43	167	41	Nov. 10, 1922
45 feet south (2 wells)	16	9	7	16	0	16	0	
50 feet south (11 wells)	432	99	333	431	1	398	33	Jan. 5, 1923
Total, 12 lines (111 wells)	2,001	440	1,561	1,335	666	951	384	
Per cent			78		33	48	19	

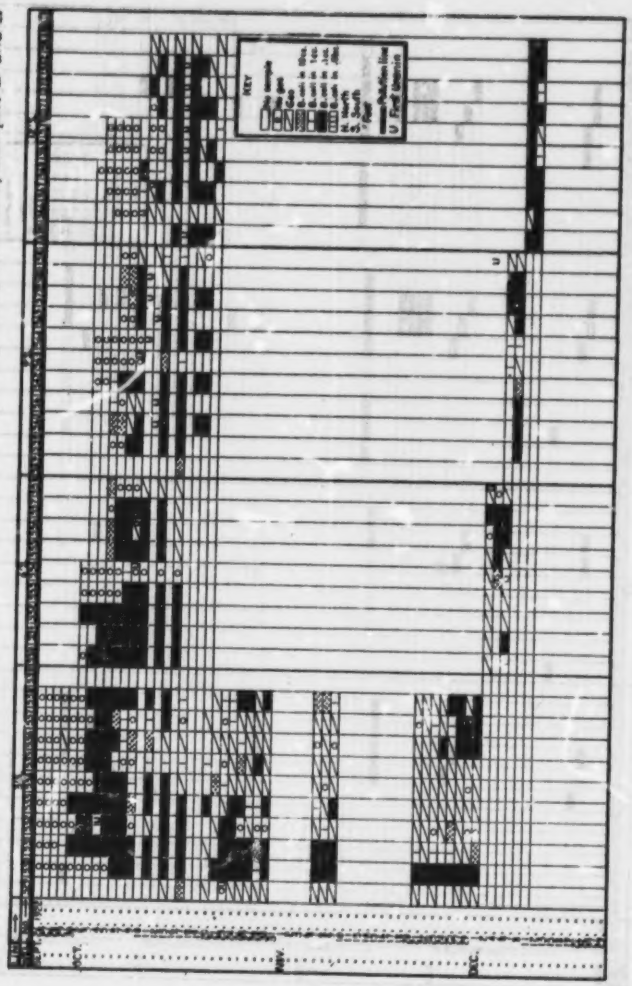
Exhibit 19.—*Summary of Group 500B by wells, Controls C, Samples D and E*

Distance from trench	Well No.	Sept. 25, 1922-May 16, 1923					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
3 feet south	529	20	2	18	19	1	1	18
	530	35	9	26	9	26	9	0
	531	37	4	33	10	27	3	7
	532	36	13	23	24	12	5	19
	533	36	4	32	17	19	4	13
	534	36	9	27	25	11	7	18
	535	39	9	30	24	15	6	18
	536	38	7	31	21	17	6	15
	537	39	11	28	22	17	7	15
	538	36	6	30	13	23	6	7
	539	14	8	6	14	0	14	0
Total		366	82	284	198	168	68	130
6 feet south	550	14	1	13	2	12	1	1
	551	11	0	11	1	10	0	1
	552	13	1	12	3	10	0	3
	553	14	5	9	8	6	5	3
	554	17	10	7	13	4	5	8
	555	13	0	13	4	9	0	4
	556	14	1	13	3	11	0	3
	557	11	1	10	2	9	1	1
	558	11	5	6	10	1	0	10
Total		118	24	94	46	72	12	34
9 feet south	559	2	0	2	1	1	0	1
	540	8	2	6	2	6	2	0
	560	12	0	12	1	11	0	1
	561	9	1	8	3	6	0	3
	562	13	2	11	3	10	2	1
	563	12	6	6	8	4	6	2
	564	17	6	11	6	11	6	0
	565	19	2	17	3	16	2	1
	579	21	0	21	0	21	0	0
	580	9	0	9	1	8	0	1
	581	12	3	9	10	2	4	6
Total		134	22	112	38	96	22	16
12 feet south	590	7	0	7	0	7	0	0
	566	12	3	9	9	3	9	0
	567	14	4	10	5	9	4	1
	568	14	5	9	5	9	5	0
	569	14	6	8	7	7	6	1
	570	15	6	9	7	8	5	2
	571	17	1	16	1	16	1	0
	572	15	0	15	1	14	0	1
	582	9	0	9	2	7	1	1
	583	9	0	9	7	2	5	2
	583a	10	8	2	10	0	10	0
Total		136	33	103	54	82	46	8
15 feet south	591	8	3	5	4	4	3	1
	573	10	1	9	8	2	3	5
	574	8	1	7	5	3	1	4
	575	4	1	3	2	2	1	1
	576	6	2	4	3	3	1	2
	584	8	1	7	1	7	1	0
	585	6	0	6	1	5	1	0
	586	7	0	7	0	7	0	0
	587	4	0	4	0	4	0	0
	588	5	0	5	3	2	0	3
Total		66	9	57	27	39	11	16
16 feet south	593	2	2	0	2	0	2	0
	594	2	0	2	2	0	2	0
	589	4	1	3	1	3	1	0
	592	5	0	5	2	3	1	1
	577	5	0	5	3	2	1	2
	578	2	1	1	1	1	1	0
Total		20	4	16	11	9	8	3

Exhibit 19.—*Summary of Group 500B by wells, Controls C, Samples D and E*—Continued

Distance from trench	Well No.	Sept. 26, 1922–May 10, 1923					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
21 feet south	796	11	1	10	3	8	2	1
	797	11	0	11	1	10	0	1
	798	11	0	11	2	9	0	2
	799	8	0	8	2	6	0	2
	801	9	2	7	8	1	7	1
	802	16	0	16	8	8	0	8
	803	16	0	16	3	13	0	3
	804	16	0	16	2	14	0	2
	805	14	0	14	1	13	0	1
	806	14	0	14	7	7	6	1
	806a	9	7	2	9	0	9	0
Total		135	10	125	46	89	24	22
30 feet south	815	12	6	6	11	1	11	0
	814	12	3	9	11	1	6	5
	813	14	4	10	13	1	12	1
	812	12	3	9	12	0	12	0
	811	17	5	12	16	1	9	7
	810	20	5	15	17	3	12	5
	809	23	5	18	13	10	4	9
	808	21	6	15	20	1	13	7
	807	20	7	13	17	3	12	5
Total		151	44	107	130	21	91	39
35 feet south	824	14	12	2	14	0	14	0
	823	13	8	5	12	1	10	2
	822	15	2	13	15	0	15	0
	821	14	13	1	14	0	14	0
	820	22	12	10	20	2	12	8
	819	21	4	17	17	4	5	12
	818	23	1	22	8	15	1	7
	817	22	2	20	15	7	6	9
	816	21	0	21	4	17	0	4
	816a	11	10	1	11	0	11	0
Total		176	64	112	130	46	88	42
40 feet south	834	19	8	11	19	0	19	0
	833	21	4	17	20	1	13	7
	832	16	3	13	16	0	16	0
	831	21	10	11	21	0	21	0
	830	22	4	18	22	0	22	0
	829	31	3	28	31	0	31	0
	828	31	2	29	30	1	20	10
	827	32	4	28	27	5	20	7
	826	26	0	26	7	19	0	7
	825	32	2	30	15	17	5	10
Total		251	40	211	208	43	167	41
45 feet south	837a	8	1	7	8	0	8	0
	836a	8	8	0	8	0	8	0
Total		16	9	7	16	0	16	0
50 feet south	844	32	5	27	32	0	32	0
	843	31	5	26	31	0	31	0
	842	36	7	29	36	0	36	0
	841	37	6	31	37	0	37	0
	840	50	13	37	50	0	50	0
	839	52	13	39	51	1	18	33
	838	47	14	33	47	0	47	0
	837	47	11	36	47	0	47	0
	836	46	9	37	46	0	46	0
	835	43	10	33	43	0	43	0
	835a	11	6	5	11	0	11	0
Total		432	99	333	431	1	398	33
Total, 111 wells (14 lines)		2,001	440	1,561	1,335	666	961	384
Per cent				78		33	48	19

EXHIBIT 20A.—*Diagram showing log of 111 wells in 14 lines of Group 500B, Controls C, Samples D and E*



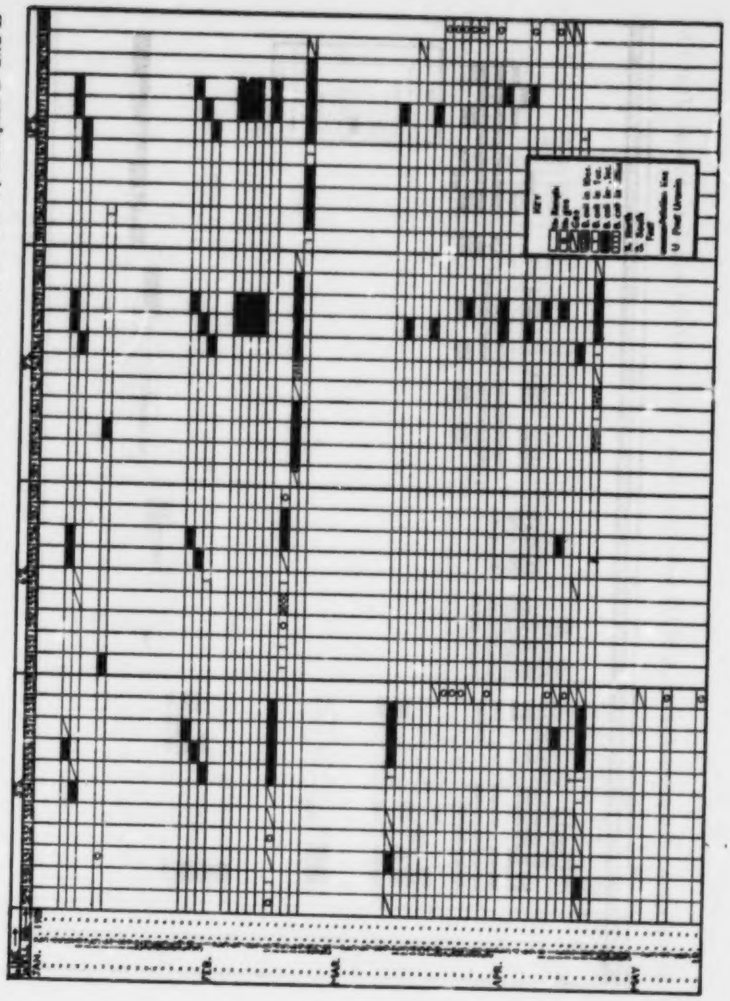


EXHIBIT 20B.—*Diagram showing log of 111 wells in 14 lines of Group 500B, Controls C, Samples D and E*

EXHIBIT 20c.—*Diagram showing log of 111 wells in 14 lines of Group 500B, Controls C, Samples D and E*

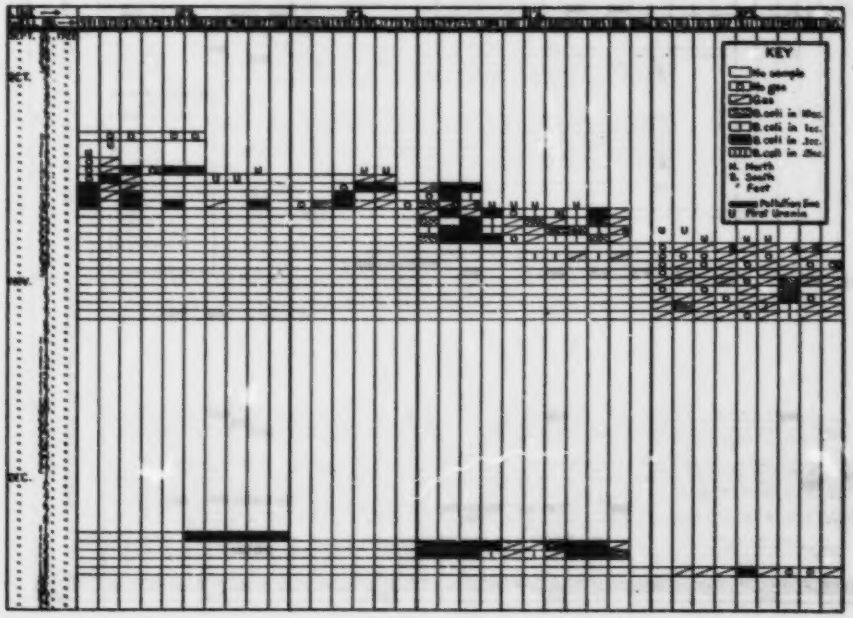
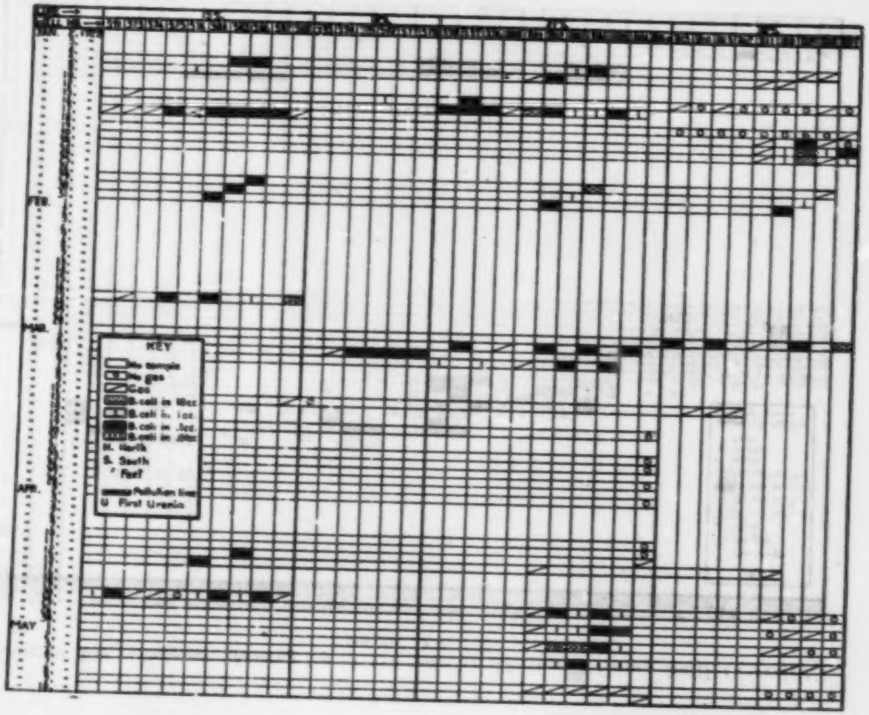


Exhibit 20d.—*Diagram showing log of 111 wells in 14 lines of Group 500B, Controls C, Samples D and E*



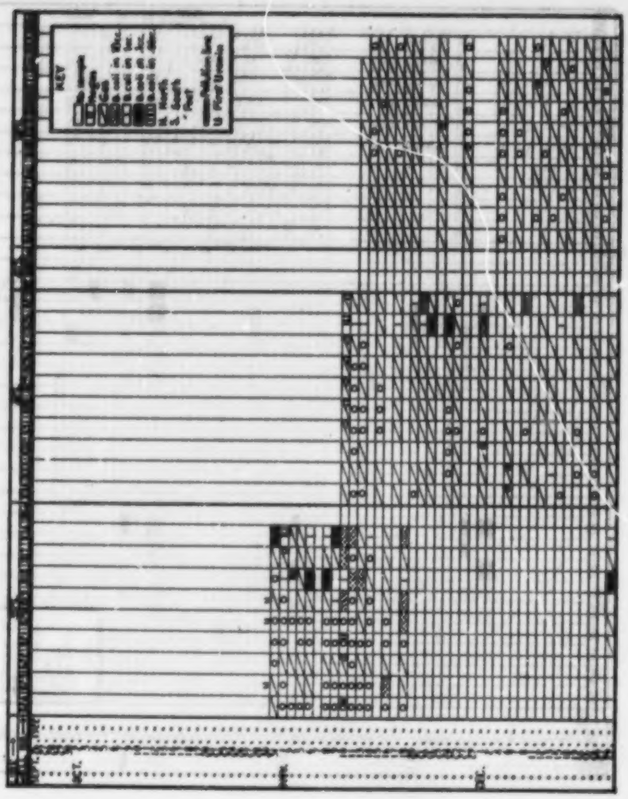


EXHIBIT 20E.—*Diagram showing log of 111 wells in 14 lines of Group 500B, Controls C, Samples D and E*

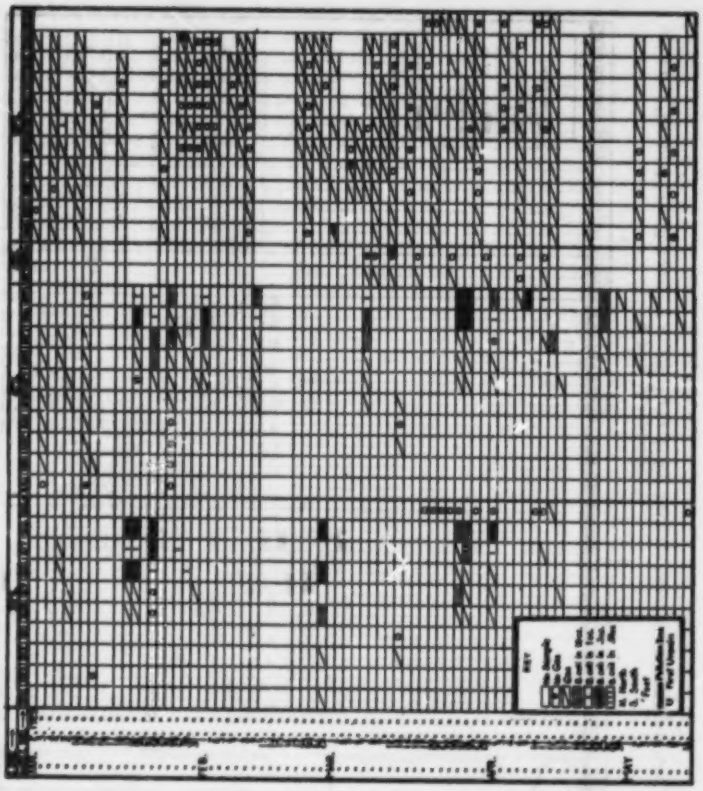


EXHIBIT 20F.—Diagram showing log of 111 wells in 14 lines of Group 500B, Controls C, Samples D and E

GROUP 600B—CONTROLS C, SAMPLES D AND E

(Bacteriological determinations by Thomson, Wales, and Alexander)

This group (Exhibit 21) contained 122 wells, Nos. A604 to A615 and 602 to 777.

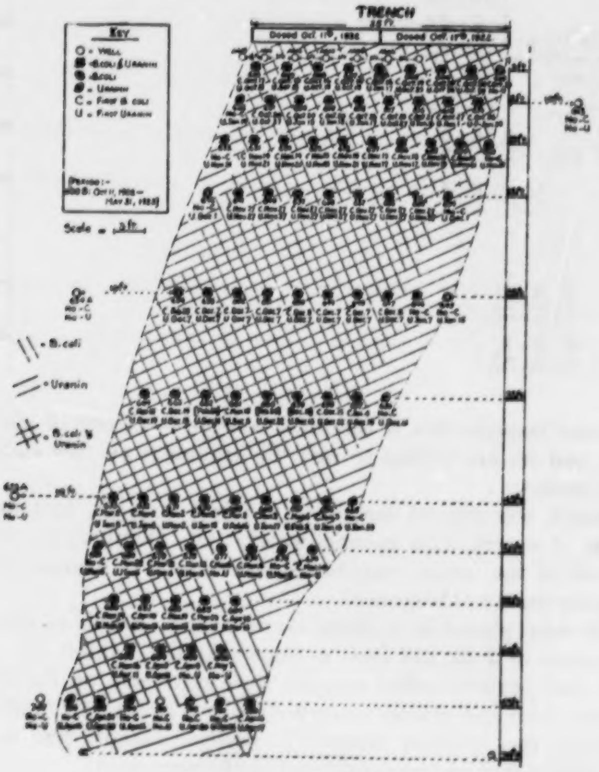
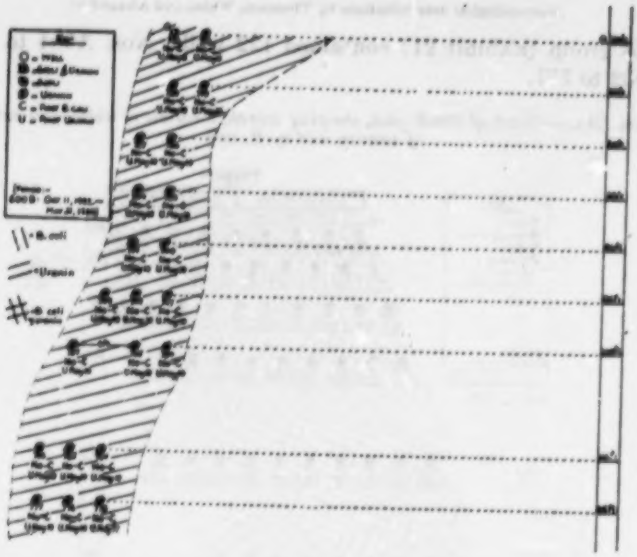

TRENCH
Key
○ = Well
= B. coli & Uranin
= B. coli
= Uranin
C = First B. coli
U = First Uranin
Period:-
Scale =
= B. coli
= Uranin
= B. coli & Uranin

Exhibit 21a.—*Chart of 600B plot, showing trench, location of wells, and extension of uranin and of B. coli*

EXHIBIT 21B.—*Chart of 600B plot, showing trench, location of wells, and extension of uranin and of B. coli*



In some respects this is the most conclusive of any of our experiments, and we are willing to rest the argument on this alone if the reader prefers.

A trench was dug 25 feet long, 1½ feet wide, ⅜ foot deep into the top of a very high ground water. On October 11, 1922, the west half of the trench was dosed with can-privy excreta (19.8 gallons) plus uranin (150 grams).

Wells were placed in 21 lines south of and parallel to this trench at distances of 2 to 125 feet, as shown in the Exhibit 21. Uranin and *B. coli* positive water samples were recovered on the 2-foot up to 65-foot lines and uranin was recovered up to the 115 (and (?) 125) foot lines; the 125-foot uranin (?) positive sample was so faintly green that it will not be considered in the argument.

From October 13, 1922, to May 31, 1923, a total of 1,313 water samples was examined from the wells of 600B; of these, 561 were gas negative, 752 (=57.27 per cent) gas positive, 896 were *B. coli* negative, and 417 (=31.75 per cent) *B. coli* positive.

A study of the details brings out the following facts:

(*a*) Immediately prior to dosing there is no Control A or Control B in the 600B group.

(*b*) In the 600A group, lines 20, 25, 30, and 35 feet, in this same field (and corresponding within a few inches at most to lines 20, 25, 30, and 35 feet of 600B), there are the following Controls C, all

B. coli negative, from May 13, 1922, to September 18, 1922: Line 20 feet, 47 samples; 25 feet, 42 samples; 30 feet, 46 samples; 35 feet, 2 samples; total, 137 samples, all *B. coli* negative. We are prepared to accept these as Controls C for this group; or, if preferred by the reader, we are willing to confine the argument to Controls A and B (see p. 17) or, if preferred, we are willing to base the argument upon the explosive appearance of *B. coli* and uranin following the dosing.

(*c*) Two days (October 13) after the dosing (October 11), *B. coli* was recovered in 1 well on the west half of the 2-foot line and in 5 wells on the west half of the 3-foot line. Uranin appeared first on October 18, when it was found in 3 wells of the 3-foot line. Prior to dosing (October 11) uranin was not present in the visible (i. e., top) ground water of the trench; it was placed in this top ground water on October 11; the conclusion would appear justified that the uranin recovered on the 3-foot line on October 18 was that placed in the top of ground water on October 11, i. e., that it came from the trench. If the reader prefers to assume that the uranin of October 18 recovered from the top ground water of the 3-foot line came from the deeper dosing of this trench on May 10, 1922, we have no objection (from the standpoint of the present argument),[3] for the uranin in that case must have traveled to the 3-foot line from a deeper layer of the trench, i. e., it came from the trench. If the unescapable fact is accepted that this uranin was of trench origin, it proves that material from the trench reached the 3-foot line; and in view of the enormous bacterial pollution of the trench on October 11, it would be difficult to assume that the *B. coli* pollution was not of the same origin as the uranin pollution. If the reader prefers to raise the point that this conclusion is not acceptable to him because of lack of *B. coli* negative samples from these identical wells immediately prior to the recovery (October 13) of *B. coli* from them, this objection is not disturbing to us; for, 4 other wells, on the east half of the 3-foot line, ran (as respects *B. coli*) daily as follows:

No. 605, negative on October 16, 17, 18, 20, and 23; but positive October 19, 21, and 24. Uranin first appeared October 23.

No. 604, negative on October 17, 18, 19, and 20; positive October 21, 23, and 24. Uranin first appeared October 26.

No. 603, negative October 17, 18, and 19; positive October 20, 21, 23, and 24. Uranin first appeared October 24.

No. 602, negative October 20; positive October 21, 23, and 24. Uranin first appeared October 26.

The east half of the trench was dosed (with 13.5 gallons of can-privy excreta plus 150 grams of uranin) on October 17, and pollution reached the wells on the east half of the 3-foot line later than pollution reached the west half of the line which was dosed October 11; further, *B. coli* negative samples are here shown for the east half of the line on the day of dosing and in one case the day before dosing; there are also several negative samples after dosing, due to the fact that the bacteria had to be carried 3 feet by the water.

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[3] As will be shown later (p. 116), however, there is serious objection to this premise from another point of view.

Thus the pollution in the wells on the west half of the 3-foot line corresponded to the time of pollution of the west half of the trench; and the delay in pollution of the wells on the east half of the 3-foot line corresponded to the delay in the dosing of the east half of the trench.

(*d*) After pollution was recovered in a given proximal line of wells its presence was confirmed for several days, then this line was sooner or later deserted in favor of more distant lines. As time went on, *B. coli* and uranin pollutions were recovered from the following lines: 6, 10, 15, 25, 35, 45, 50, 55, 60, and 65 feet, while uranin alone was recovered from more distant lines, namely, 70, 75, 80, 85, 90, 95, 100, 110, 115, and (?) 125 feet.

(*e*) It will be recalled (p. 32), that in the 600A group (the same plot of ground used for the 600B group), *B. coli* pollution was not traced beyond the 8-foot line except in two samples of the 16-foot line.

The 10-foot line of 600A showed *B. coli* negative in all 83 samples taken (namely, June 1 to July 26, 1922); this same line (at least within a few inches at most) showed 83 *B. coli* positive samples among the total 142 samples (600B) taken November 13, 1922, to March 13, 1923.

The 12-foot line of 600A showed only *B. coli* negative (total number of samples 91) June 5 to July 27, 1922; samples are lacking from this line in 600B.

The 14-foot line of 600A showed only *B. coli* negative (total number of samples 77) June 6 to July 28, 1922; samples are lacking from this line in 600B.

The 16-foot line of 600A showed 2 *B. coli* positive samples and 52 *B. coli* negatives June 9 to July 28, 1922.

Thus it will be noticed that three lines of wells (10, 12, and 14 feet) immediately proximal to the 15-foot line were *B. coli* negative in all samples (total 251) June 1 to September 28, 1922.

The 15-foot line (600B) showed 57 *B. coli* positives in a total of 91 samples November 27, 1922, to March 13, 1923. Accordingly, this line became seriously polluted (600B) after the lines immediately preceding it had run negative (600A).

The 20-foot line of 600A showed only *B. coli* negative (total, 45 samples) June 13 to July 24, 1922; samples not taken for 600B.

The 25-foot line of 600A showed only *B. coli* negative (total, 42 samples) June 20 to July 25, 1922; this same line in the 600B experiment showed 47 *B. coli* positives in a total of 98 samples December 7, 1922, to April 10, 1923; accordingly, the line became polluted.

The 30-foot line of 600A showed only *B. coli* negative (total, 46 samples) June 27 to September 18, 1922; samples not taken for 600B.

The 35-foot line of 600A showed 2 *B. coli* negative samples July 17 to 25, 1922; this same line showed 23 *B. coli* positives in a total of 198 samples December 8, 1922, to March 15, 1923. Accordingly, the 35-foot line had become polluted in 600B after all samples (total, 90) from the 25, 30, and 35 foot lines May 20 to September 18, 1922, had shown negative.

In the 600B experiment, line 45 feet, showed 21 *B. coli* positives and 110 negatives January 3 to April 10, 1923; line 50 feet, 24 *B. coli* positives, 30 negatives, March 6 to May 21, 1923; line 55 feet, 28 *B. coli* positives, 40 *B. coli* negatives, March 15 to May 17, 1923; line 60 feet, 13 *B. coli* positives, 34 negatives, March 28 to May 16, 1923; line 65 feet, 6 *B. coli* positives, 170 negatives, April 16 to May 31, 1923.

All samples beyond 65 feet were *B. coli* negatives; 70 feet, 9; 75 feet, 10; 80 feet, 8; 85 feet, 10; 90 feet, 10; 95 feet, 15; 100 feet, 12; 110 feet, 9; 115 feet, 9; total, 92 samples, May 8 to 23, 1923.

The conclusion is inevitable that following the pollution of the 600B trench on October 11 and October 17, 74 wells became *B. coli* positive, 48 wells remained *B. coli* negative (so far as the samples showed); in the area of the 2 to 65 foot lines 74 wells were *B. coli* positive against 25 wells negative (so far as the number of samples revealed); as uranin appeared in all of the well lines which were *B. coli* positive and even beyond the *B. coli* positive lines, the conclusion can not be escaped that uranin pollution from the 600 trench extended to the wells, and if this conclusion is accepted as established in respect to uranin it is to be accepted as respects *B. coli;* the 600B trench was the nearest place of known pollution to the 600B wells; to assume that the pollution of these wells is from any other trench is to assume that it came from a greater distance and not in line with the ground-water flow; to assume that it was washed down from the surface to the ground water is not in harmony with the subaverage rainfall and is negatived by the lines 70 to 115 feet, which were in reality in part on lower ground.

The question whether this pollution following the 600B dosing came from this dosing on October 11 and 17 or from the earlier dosing of 600A (May 10) is not the point at immediate issue. The proof is considered conclusive that *B. coli* and uranin pollution extended from the 600 trench to the 600B wells.

The detailed data for lines and wells are shown in Exhibits 22 to 24.

Exhibit 22.—*Summary of Group 600B by lines, Controls C, Samples D and E*

Total by lines	Oct. 11, 1922–May 31, 1923					Controls C	Samples D	B. coli first recovered
	Number of samples	Gas		B. coli				
		Absent	Present	Absent	Present (Samples E)			
2 feet south (7 wells)	7	0	7	6	1	2	4	Oct. 18, 1922
3 feet south (9 wells)	89	0	89	39	50	12	27	Oct. 26, 1922
6 feet south (10 wells)	120	14	106	56	64	20	36	Oct. 30, 1922
10 feet south (10 wells)	142	10	132	59	83	24	35	Nov. 13, 1922
15 feet south (9 wells)	91	18	73	34	57	17	17	Nov. 27, 1922
20 feet south (11 wells)	98	35	63	51	47	30	21	Dec. 7, 1922
35 feet south (9 wells)	198	108	90	175	23	130	26	Dec. 15, 1922
45 feet south (10 wells)	131	60	71	110	21	94	16	Jan. 8, 1923
50 feet south (6 wells)	54	19	35	20	34	28	2	Mar. 6, 1923
55 feet south (5 wells)	68	32	36	40	28	20	13	Mar. 19, 1923
60 feet south (4 wells)	47	29	18	34	13	26	5	Apr. 2, 1923
65 feet south (9 wells)	170	162	8	170	0	130	22	Apr. 16, 1923
70 feet south (2 wells)	9	9	0	9	0	9	0	
75 feet south (2 wells)	10	10	0	10	0	10	0	
80 feet south (2 wells)	8	3	5	8	0	8	0	
85 feet south (2 wells)	10	10	0	10	0	10	0	
90 feet south (2 wells)	10	10	0	10	0	10	0	
95 feet south (3 wells)	15	11	4	15	0	15	0	
100 feet south (2 wells)	12	12	0	12	0	12	0	
110 feet south (3 wells)	9	1	8	9	0	9	0	
115 feet south (3 wells)	9	1	8	9	0	9	0	
Total, 21 lines (122 wells)	1,313	561	752	896	417	650	246	
Per cent			57		32	50	18	

Exhibit 23.—*Summary of Group 600B, by wells*

Distance from trench	Well No.	Oct. 11, 1922–May 31, 1923					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
2 feet south	A-615	1	0	1	1	0	0	1
	A-614	1	0	1	1	0	0	1
	A-612	1	0	1	0	1	0	0
	A-610	1	0	1	1	0	0	1
	A-608	1	0	1	1	0	1	0
	A-606	1	0	1	1	0	0	1
	A-604	1	0	1	1	0	1	0
Total		7	0	7	6	1	2	4
3 feet south	610	9	0	9	3	6	1	2
	609	10	0	10	6	4	0	6
	608	10	0	10	4	6	0	4
	607	11	0	11	2	9	0	2
	606	11	0	11	4	7	0	4
	605	12	0	12	5	7	3	2
	604	11	0	11	8	3	4	4
	603	10	0	10	5	5	3	2
	602	5	0	5	2	3	1	1
Total		89	0	89	39	50	12	27
6 feet south	622	10	7	3	10	0	10	0
	621	13	0	13	3	10	0	3
	620	13	0	13	3	10	0	3
	619	15	0	15	7	8	0	7
	618	13	0	13	8	5	1	7
	617	14	0	14	4	10	0	4
	616	13	0	13	8	5	1	7
	615	12	0	12	3	9	1	2
	614	10	0	10	3	7	0	3
	613	7	7	0	7	0	7	0
Total		120	14	106	56	64	20	36

EXHIBIT 23.—*Summary of Group 600B, by wells*—Continued

Distance from trench	Well No.	Oct. 11, 1922-May 31, 1923					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
10 feet south	632	13	6	7	13	0	13	0
	631	13	1	12	2	11	0	2
	630	13	0	13	2	11	0	2
	629	15	0	15	2	13	0	2
	628	15	1	14	5	10	0	5
	627	16	0	16	6	10	0	6
	626	18	0	18	9	9	0	9
	625	15	0	15	3	12	0	3
	624	13	2	11	6	7	0	6
	623	11	0	11	11	0	11	0
Total		142	10	132	59	83	24	35
15 feet south	642	8	6	2	8	0	8	0
	641	9	1	8	2	7	0	2
	640	9	0	9	0	9	0	0
	639	10	0	10	0	10	0	0
	638	10	1	9	1	9	0	1
	637	13	0	13	0	13	0	0
	636	13	2	11	9	4	0	9
	635	10	2	8	5	5	0	5
	634	9	6	3	9	0	9	0
Total		91	18	73	34	57	17	17
25 feet south	654a	8	8	0	8	0	8	0
	654	6	4	2	5	1	5	0
	653	8	0	8	3	5	0	3
	652	8	0	8	0	8	0	0
	651	9	0	9	1	8	0	1
	650	9	3	6	4	5	1	3
	649	13	3	10	4	9	0	4
	648	13	5	8	7	6	0	7
	647	9	2	7	4	5	1	3
	646	8	7	1	8	0	8	0
	645	7	4	3	7	0	7	0
Total		98	36	62	51	47	30	21
35 feet south	664	20	18	2	19	1	19	0
	663	22	4	18	20	2	6	14
	662	22	6	16	19	3	19	0
	661	23	20	3	22	1	22	0
	660	22	17	5	21	1	21	0
	659	24	17	7	18	6	18	0
	658	24	15	9	20	4	3	17
	657	21	4	17	16	5	11	5
	656	20	7	13	20	0	20	0
Total		198	108	90	175	23	139	36
45 feet south	673a	8	8	0	8	0	8	0
	673	12	10	2	11	1	8	3
	672	12	8	4	10	2	9	1
	671	13	7	6	11	2	9	2
	670	14	9	5	11	3	10	1
	669	14	4	10	11	3	10	1
	668	18	5	13	14	4	14	0
	667	16	5	11	15	1	14	1
	666	12	3	9	7	5	0	7
	665	12	1	11	12	0	12	0
Total		131	60	71	110	21	94	16
50 feet south	681	8	4	4	8	0	8	0
	680	7	3	4	5	2	5	0
	679	7	4	3	4	3	3	1
	678	7	1	6	3	4	3	0
	677	7	0	7	0	7	0	0
	676	7	1	6	1	6	0	1
	675	6	5	1	6	0	6	0
	674	5	1	4	3	2	3	0
Total		54	19	35	30	24	28	2

Exhibit 23.—*Summary of Group 600B, by wells*—Continued

Distance from trench	Well No.	Oct. 11, 1922-May 31, 1923					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
55 feet south	688 687 686 685 684	14 14 13 12 15	9 8 1 5 9	5 6 12 7 6	10 12 1 6 11	4 2 12 6 4	1 10 1 5 11	9 2 0 1 0
Total		68	32	36	40	28	28	12
60 feet south	695 694 693 692	11 12 12 12	10 5 4 10	1 7 8 2	10 5 9 10	1 7 3 2	10 2 4 10	0 3 5 0
Total		47	29	18	34	13	26	8
65 feet south	707 706 705 704 703 702 701 700	22 22 22 22 22 22 22 22	22 22 17 22 22 21 22 20	0 0 5 0 0 1 0 2	22 22 17 22 22 22 22 21	0 0 5 0 0 0 0 1	22 22 6 22 22 22 22 0	0 0 11 0 0 0 0 21
Total		176	168	8	170	6	138	32
70 feet south	713 712	4 5	4 5	0 0	4 5	0 0	4 5	0 0
Total		9	9	0	9	0	9	0
75 feet south	720 719	5 5	5 5	0 0	5 5	0 0	5 5	0 0
Total		10	10	0	10	0	10	0
80 feet south	727 726	4 4	0 3	4 1	4 4	0 0	4 4	0 0
Total		8	3	5	8	0	8	0
85 feet south	734 733	5 5	5 5	0 0	5 5	0 0	5 5	0 0
Total		10	10	0	10	0	10	0
90 feet south	741 740	5 5	5 5	0 0	5 5	0 0	5 5	0 0
Total		10	10	0	10	0	10	0
95 feet south	749 748 747	5 5 5	3 3 5	2 2 0	5 5 5	0 0 0	5 5 5	0 0 0
Total		15	11	4	15	0	15	0
100 feet south	757 755 754	4 4 4	4 4 4	0 0 0	4 4 4	0 0 0	4 4 4	0 0 0
Total		12	12	0	12	0	12	0
110 feet south	766 765 764	3 3 3	0 1 0	3 2 3	3 3 3	0 0 0	3 3 3	0 0 0
Total		9	1	8	9	0	9	0
115 feet south	777 776 775	3 3 3	1 0 0	2 3 3	3 3 3	0 0 0	3 3 3	0 0 0
Total		9	1	8	9	0	9	0
Total 122 wells (21 lines)		1,313	561	752	896	417	650	246

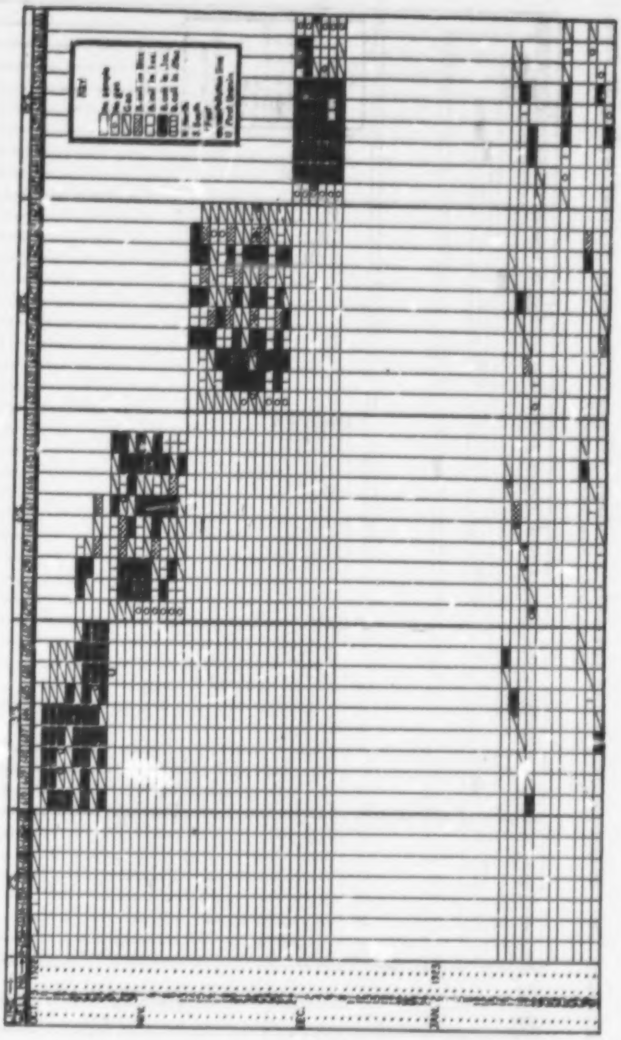


EXHIBIT 24A.—*Diagram showing log of 122 wells in 21 lines of Group 600B, October 11, 1922, to May 31, 1923, Controls C, Samples D and E*

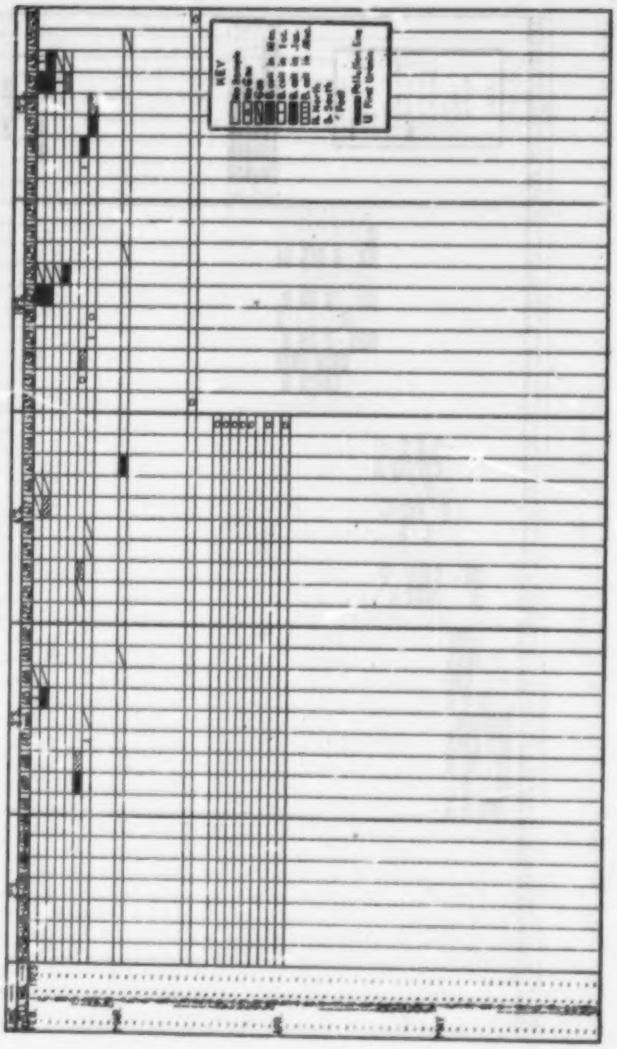


EXHIBIT 24B.—*Diagram showing log of 122 wells in 21 lines of Group 600B, October 11, 1922, to May 31, 1923, Controls C, Samples D and E*

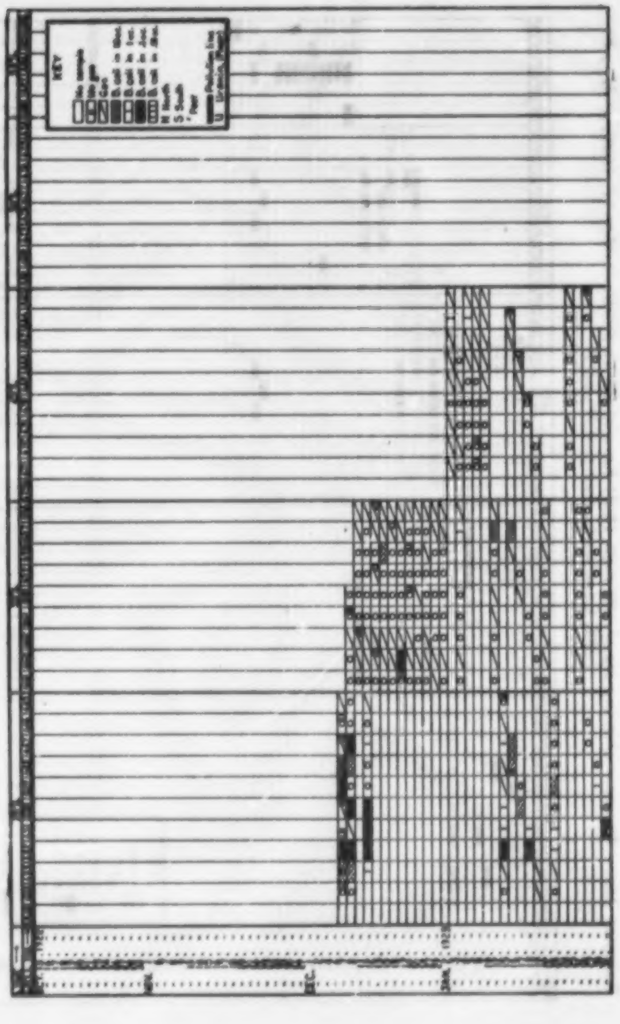
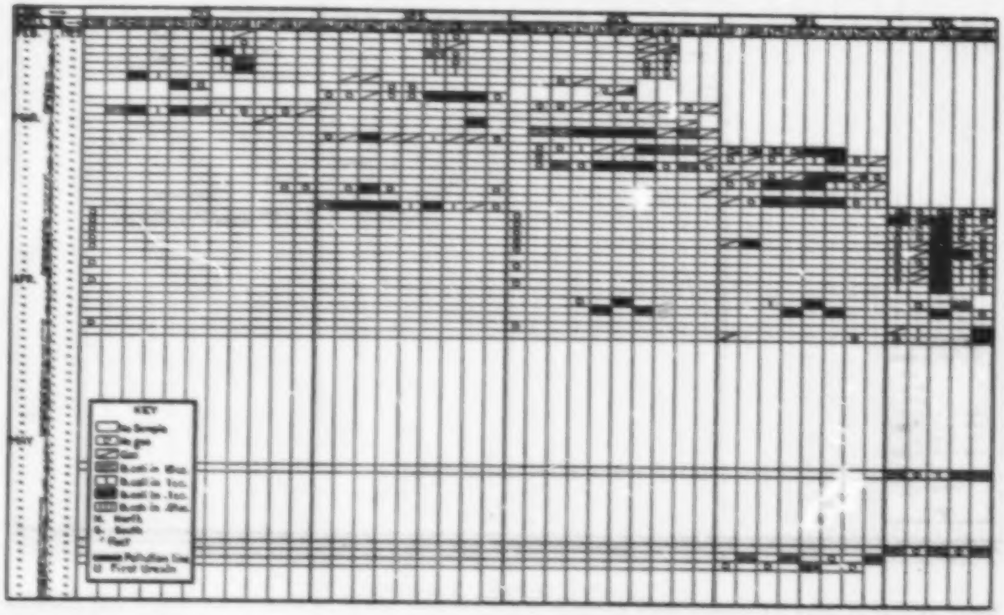


EXHIBIT 24c.—*Diagram showing log of 122 wells in 21 lines of Group 600B, October 11, 1922, to May 31, 1923, Controls C, Samples D and E*

EXHIBIT 24D.—*Diagram showing log of 128 wells in 21 lines of Group 600B, October 11, 1922, to May 31, 1923, Controls C, Samples D and E*



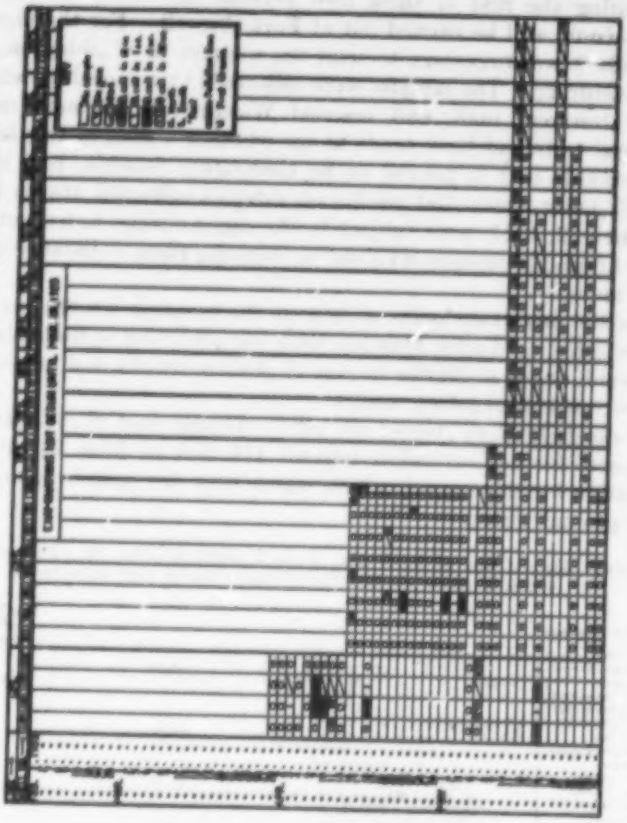


EXHIBIT 24B.—*Diagram showing log of 128 wells in 21 lines of Group 600B, October 11, 1922, to May 31, 1923, Controls C, Samples D and E*

LATER EXTENSION OF POLLUTION IN GROUP 600B (JUNE 1, 1923, TO JUNE 22, 1925)

Financial considerations necessitated an interruption of observations, and after May 31, 1923, it was impossible to collect samples regularly and at frequent intervals. It was, however, possible to collect samples at four periods and thus to obtain data on the status (Exhibit 25) of the pollution as follows:

June 1, 1923, to August 30, 1923.
March 5, 1924, to July 25, 1924.
December 6, 1924, to January 12, 1925.
May 9, 1925, to June 22, 1925.

During the first of these four periods the entire bacteriological work could still be carried out at Fort Caswell. For the three later periods it was necessary to send the samples to Washington, D. C., for culturing. The samples were collected in the morning, sent off in the afternoon mail, and reached Washington the next morning. Several tests had been made to see whether a plan of this kind was practicable and it proved to be thoroughly feasible, but the academic point exists that results on samples collected March 5, 1924, to June 22, 1925, were subject to the slight change in bacteriological (not uranin) technique involved in shipping them a distance of about 400 miles.

As the important point at issue is the question whether or not the pollution spread after May 31, 1923, our own view is that this change of technique is negligible in case of *positive* results and not of special importance in negative results.

June 1, 1923, to August 30, 1923.—Uranin and *B. coli* results (as respects further extension beyond 115 feet of May 31, 1923) are negative for this period, which was a very dry season, hence one of low ground water.

EXHIBIT 25A.—*Chart of 600B plot, June 1, 1923, to June 22, 1925, showing the status of pollution after the intensive studies were terminated*

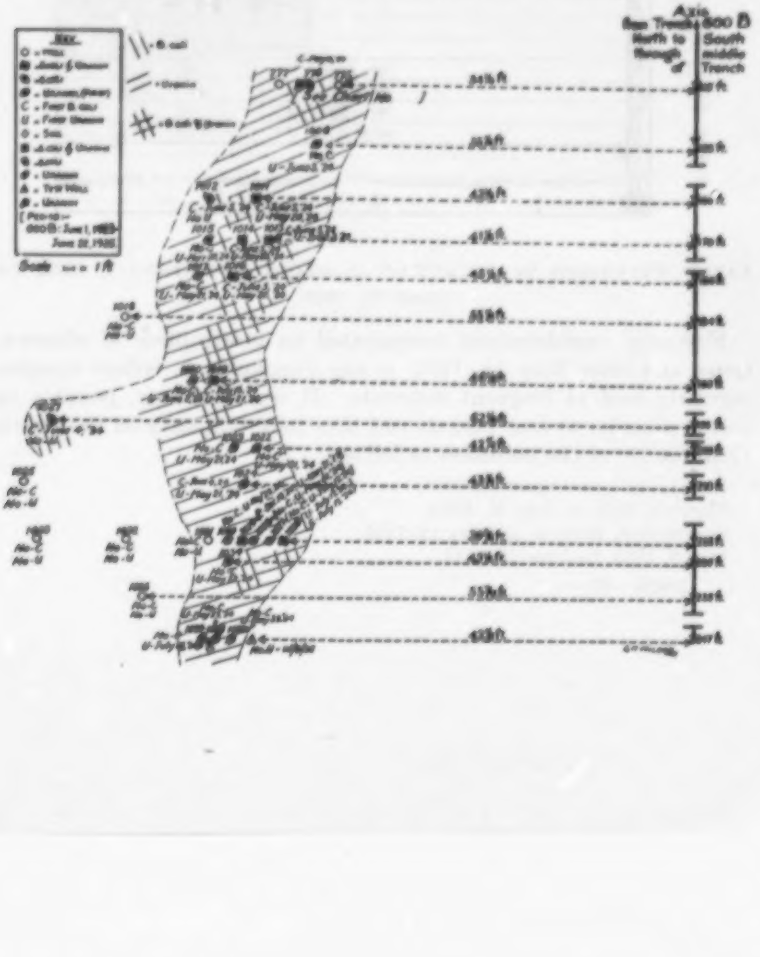
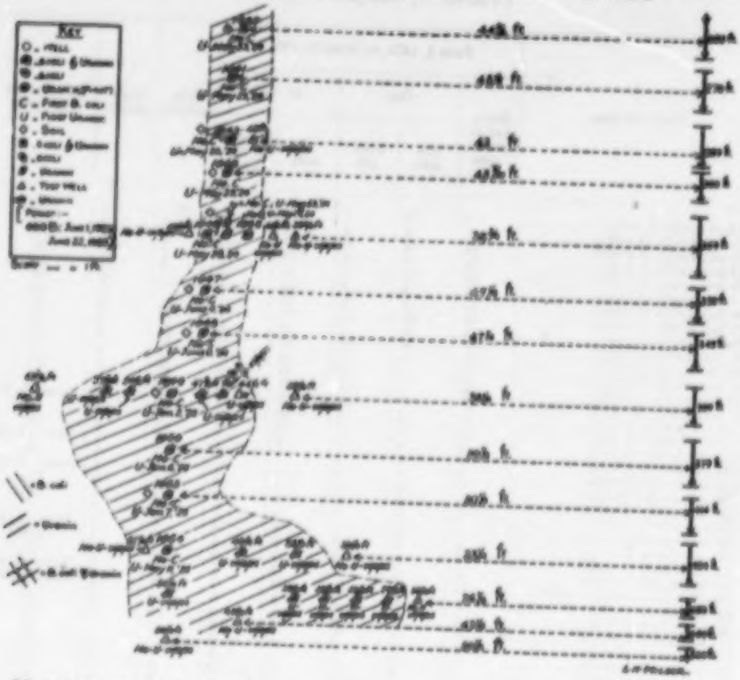


Exhibit 25b.—*Chart of 600B plot, June 1, 1923, to June 22, 1925, showing the status of pollution after the intensive studies were terminated*



March 5, 1924, to July 25, 1924.—Uranin was found up to the 349-foot line and *B. coli* was recovered in lines 65 feet, 115 feet, 166 feet, 170 feet, 180 feet, 190 feet, 195 feet, 210 feet, and 228 (232) feet.

December 6, 1924 to January 12, 1925.—Uranin was found up to the 414-foot line, and *B. coli* was recovered in lines 170 feet and 228 (232 diagonal) feet.

May 9, 1925 to June 22, 1925.—Uranin was found up to lines 424 feet and 450 feet (both lines were accessible only at low tide and were covered by high tide). *B. coli* was recovered from water samples only on the 60-foot and 95-foot lines, but from soil samples (see p. 81), up to the 115-foot line.

The detailed results are given in Exhibits 26 to 28.

Exhibit 26.—*Summary of Group 600B by lines, June 1, 1933, to June 28, 1935, Controls C, Samples D and E*

Total by lines	June 1, 1933, to June 28, 1935					Controls C[1]	Samples D	B. coli first recovered
	Number of samples	Gas		B. coli				
		Absent	Present	Absent	Present (Samples E)			
5 feet south (1 well)	1	0	1	1	0	(2)	1	(3)
15 feet south (5 wells)	6	4	2	6	0	2	4	(3)
25 feet south (9 wells)	24	14	10	21	0	3	16	(3)
45 feet south (9 wells)	30	16	14	21	9	3	19	(3)
50 feet south (8 wells)	17	14	3	15	2	2	11	(3)
55 feet south (5 wells)	14	9	5	12	2	4	12	(3)
60 feet south (4 wells)	12	4	8	12	2	--------	12	(3)
65 feet south (8 wells)	20	4	16	16	4	20	17	(3)
70 feet south (2 wells)	16	10	6	16	4	16	0	(3)
75 feet south (2 wells)	17	5	12	17	0	17	0	(4)
80 feet south (2 wells)	14	9	5	14	0	14	0	(4)
85 feet south (2 wells)	15	8	7	15	0	13	0	(4)
90 feet south (2 wells)	16	7	9	16	0	16	0	(4)
95 feet south (2 wells)	17	9	8	16	0	16	0	(4)
100 feet south (3 wells)	18	5	13	18	1	16	0	June 18, 1935
110 feet south (3 wells)	12	6	6	13	0	13	0	(4)
115 feet south (3 wells)	9	4	5	8	0	7	0	(4)
127 feet south (1 well)	1	0	1	1	1	1	1	May 16, 1934
164 feet south (2 wells)	4	0	4	1	0	0	0	(4)
170 feet south (3 wells)	9	0	9	6	3	8	1	June 5, 1934
180 feet south (2 wells)	5	0	5	5	3	2	8	Do.
184 feet south (1 well)	3	0	3	2	3	3	1	Do.
190 feet south (2 wells)	6	0	6	4	0	1	0	(4)
195 feet south (1 well)	2	0	2	2	2	0	3	June 4, 1934
203 feet south (2 wells)	6	0	6	6	1	6	2	Do.
210 feet south (2 wells)	3	2	1	2	0	3	0	(4)
228 (232) feet south (8 wells)	26	6	20	25	1	20	0	June 4, 1934
230 feet south (1 well)	3	0	3	3	2	3	2	July 17, 1934
235 feet south (1 well)	3	0	3	3	0	3	0	(4)
247 feet south (3 wells)	14	1	13	14	0	14	0	(4)
260 feet south (1 well)	4	0	4	4	0	4	0	(4)
270 feet south (1 well)	1	0	1	1	0	1	0	(4)
289 feet south (1 well)	5	0	5	5	0	5	0	(4)
300 feet south (1 well)	5	0	5	5	0	5	0	(4)
320 feet south (2 wells)	9	3	6	9	0	9	0	(4)
330 feet south (1 well)	6	3	3	6	0	6	0	(4)
340 feet south (1 well)	5	3	2	5	0	5	0	(4)
350 feet south (1 well)	2	0	2	2	0	2	0	(4)
370 feet south (1 well)	3	0	3	3	0	2	0	(4)
414 feet south (1 well)	3	0	3	3	0	2	0	(4)
494 feet south (1 well)	1	0	1	1	0	1	0	(4)
Total, 41 lines (112 wells)	433	188	246	396	37	279	107	--------
Per cent	--------	--------	57	--------	9	--------	--------	--------

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[1] Numerical values for this exhibit.

[2] No Control C for dates of this exhibit.

[3] See Exhibit 24.

[4] No B. coli.

EXHIBIT 27.—*Summary of Group 600B, by wells, June 1, 1933, to June 28, 1935, Controls C, Samples D and E*

Distance from trench	Well No.	June 1, 1933, to June 28, 1935					Controls C[2]	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
2 feet south	697	1	0	1	1	0	([2])	1
15 feet south	642	1	1	0	1	0	1	0
	[illegible]	1	0	1	1	0	....	1
	[illegible]	2	1	1	2	0	....	2
	[illegible]	1	1	0	1	0	....	1
	[illegible]	1	1	0	1	0	1	0
Total	....	6	4	2	6	0	2	4
35 feet south	664	3	2	1	3	0	....	3
	663	2	1	1	1	1	....	1
	662	3	1	2	2	1	....	2
	661	2	1	1	1	1	....	1
	660	4	2	2	4	0	....	4
	659	3	2	1	2	0	....	2
	658	3	2	1	3	0	....	3
	657	3	3	0	2	0	....	3
	656	3	2	1	3	0	3	0
Total	....	26	16	10	21	3	3	19
45 feet south	673	3	2	1	3	0	....	3
	672	3	2	1	2	1	....	2
	671	4	3	1	4	0	....	4
	670	3	0	3	0	3	....	0
	669	5	2	3	3	2	....	3
	668	3	0	3	1	2	....	1
	667	4	4	0	4	0	....	4
	666	3	2	1	2	1	....	2
	665	2	1	1	2	0	3	0
Total	....	30	16	14	21	9	3	19
50 feet south	681	2	2	0	2	0	2	0
	680	2	2	0	2	0	....	2
	679	2	2	0	2	0	....	2
	678	2	2	0	2	0	....	2
	677	2	2	0	2	0	....	2
	676	3	1	2	2	1	....	2
	675	2	2	0	2	0	2	0
	674	2	1	1	1	1	....	1
Total	....	17	14	3	15	2	4	11
55 feet south	688	3	2	1	3	0	....	3
	687	2	2	0	2	0	....	2
	686	4	2	2	3	1	....	3
	685	2	2	0	2	0	....	2
	684	3	1	2	2	1	....	2
Total	....	14	9	5	12	2	....	12
60 feet south	695	3	1	2	3	0	....	3
	694	4	1	3	3	1	....	3
	693	3	1	2	3	0	....	3
	692	3	1	2	3	0	....	3
Total	....	13	4	9	12	1	....	12
65 feet south	707	8	5	3	6	2	5	1
	706	8	8	0	8	0	8	0
	705	8	6	2	8	0	....	8
	704	7	6	1	7	0	7	0
	703	7	5	2	7	0	7	0
	702	7	5	2	6	1	5	1
	701	8	6	2	7	1	6	1
	700	6	3	3	6	0	....	6
Total	....	59	44	15	55	4	38	17

[1] Numerical values for this exhibit.

[2] No Control C for the dates of this exhibit.

EXHIBIT 27.—*Summary of Group 800B, by wells, June 1, 1923, to June 22, 1925, Controls C, Samples D and E*—Continued

Distance from trench	Well No.	June 1, 1925, to June 22, 1925					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
70 feet south	713 712	8 8	5 5	3 3	8 8	0 0	8 8	0 0
Total	....	16	10	6	16	0	16	0
75 feet south	720 719	8 9	3 2	5 7	8 9	0 0	8 9	0 0
Total	....	17	5	12	17	0	17	0
80 feet south	727 726	6 8	4 5	2 3	6 8	0 0	6 8	0 0
Total	....	14	9	5	14	0	14	0
85 feet south	734 733	6 7	3 5	3 2	6 7	0 0	6 7	0 0
Total	....	13	8	5	13	0	13	0
90 feet south	741 740	7 9	2 5	5 4	7 9	0 0	7 9	0 0
Total	....	16	7	9	16	0	16	0
95 feet south	749 748 747	5 6 6	2 2 5	3 4 1	4 6 6	1 0 0	4 6 6	0 0 0
Total	....	17	9	8	16	1	16	0
100 feet south	757 755 754	4 6 8	1 2 2	3 4 6	4 6 8	0 0 0	4 6 8	0 0 0
Total	....	18	5	13	18	0	18	0
110 feet south	766 765 764	2 5 6	1 3 2	1 2 4	2 5 6	0 0 0	2 5 6	0 0 0
Total	....	13	6	7	13	0	13	0
115 feet south	777 776 775	3 3 3	1 1 2	2 2 1	3 2 3	0 1 0	3 1 3	0 1 0
Total	....	9	4	5	8	1	7	1
125 feet south	1,006	1	0	1	1	0	1	0
166 feet south	1,012 1,011	2 2	0 0	2 2	0 1	2 1	0 0	0 1
Total	....	4	0	4	1	3	0	1
170 feet south	1,015 1,014 1,013	3 3 3	0 0 0	3 3 3	3 2 1	0 1 2	3 0 0	0 2 1
Total	....	9	0	9	6	3	3	3
180 feet south	1,017 1,016	2 3	0 0	2 3	2 1	0 2	2 0	0 1
Total	....	5	0	5	3	2	2	1
184 feet south	1,018	2	0	2	2	0	2	0
190 feet south	1,020 1,019	3 3	0 0	3 3	2 2	1 1	0 1	2 1
Total	....	6	0	6	4	2	1	3

EXHIBIT 27.—*Summary of Group 600B, by wells, June 1, 1933, to June 28, 1935, Controls C, Samples D and E*—Continued

Distance from trench	Well No.	June 1, 1933, to June 28, 1935					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
195 feet south	[illegible]	3	0	3	2	1	0	3
203 feet south	[illegible]	3	0	3	3	0	3	0
	[illegible]	3	0	3	3	0	3	0
Total		6	0	6	6	0	6	0
210 feet south	[illegible]	2	2	0	2	0	2	0
	[illegible]	1	0	1	0	1	0	0
Total		3	2	1	2	1	2	0
226 (232) feet south	1,033	2	0	2	2	0	2	0
	1,032	2	0	2	2	0	2	0
	1,031	3	1	2	3	0	3	0
	1,030	3	0	3	3	0	3	0
	1,029	4	1	3	3	1	3	0
	1,028	3	1	2	3	0	3	0
	1,027	3	1	2	3	0	3	0
	1,026	4	0	4	3	1	1	3
Total		24	4	20	22	2	20	3
230 feet south	1,034	3	0	3	3	0	3	0
235 feet south	1,035	3	0	3	3	0	3	0
247 feet south	1,039	4	0	4	4	0	4	0
	4,038	5	0	5	5	0	5	0
	1,037	5	1	4	5	0	5	0
Total		14	1	13	14	0	14	0
260 feet south	1,040	4	0	4	4	0	4	0
270 feet south	1,041	1	0	1	1	0	1	0
280 feet south	1,042	5	0	5	5	0	5	0
300 feet south	1,043	5	0	5	5	0	5	0
339 feet south	1,046	2	1	1	2	0	2	0
	1,044	3	1	2	3	0	3	0
	1,045	4	1	3	4	0	4	0
Total		9	3	6	9	0	9	0
330 feet south	1,047	6	3	3	6	0	6	0
340 feet south	1,048	5	3	2	5	0	5	0
350 feet south	1,049	2	0	2	2	0	2	0
370 feet south	1,050	3	0	3	3	0	3	0
414 feet south	1,053	3	0	3	3	0	3	0
434 feet south	1,054	1	0	1	1	0	1	0

Exhibit 28a.—*Diagram showing log of 113 wells in 41 lines, Group 600B, June 1, 1933, to June 22, 1935, Controls C, Samples D and E*

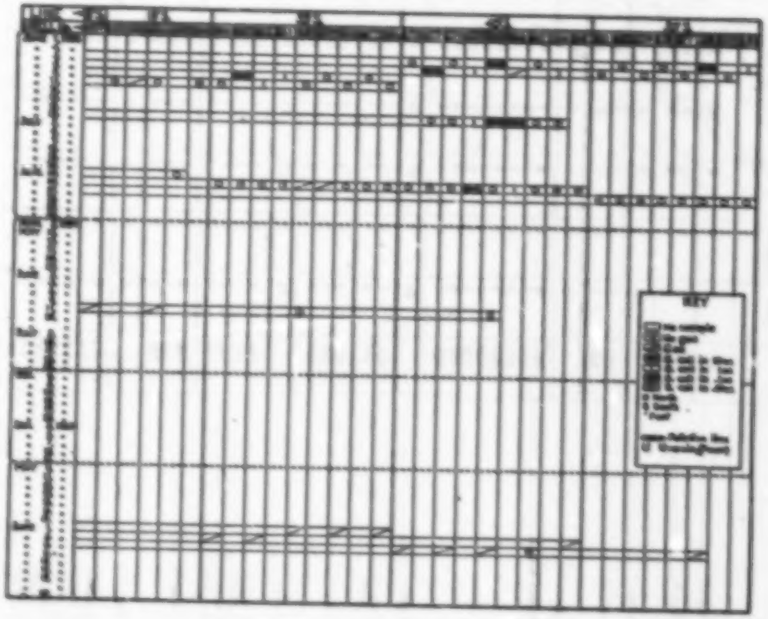


EXHIBIT 28a.—*Diagram showing log of 113 wells in 41 lines, Group 6-08, June 1, 1933, to June 22, 1935, Controls C, Samples D and E*

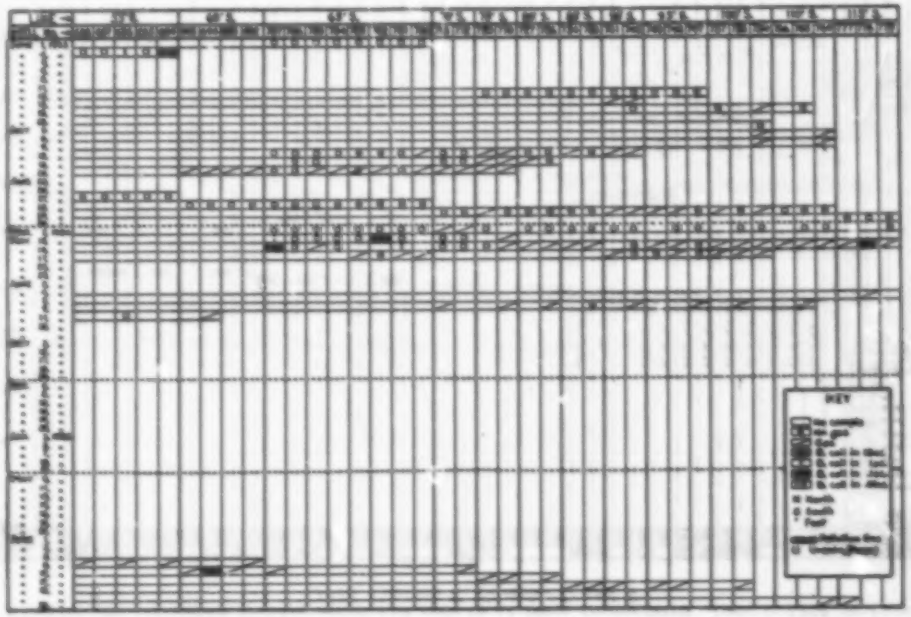
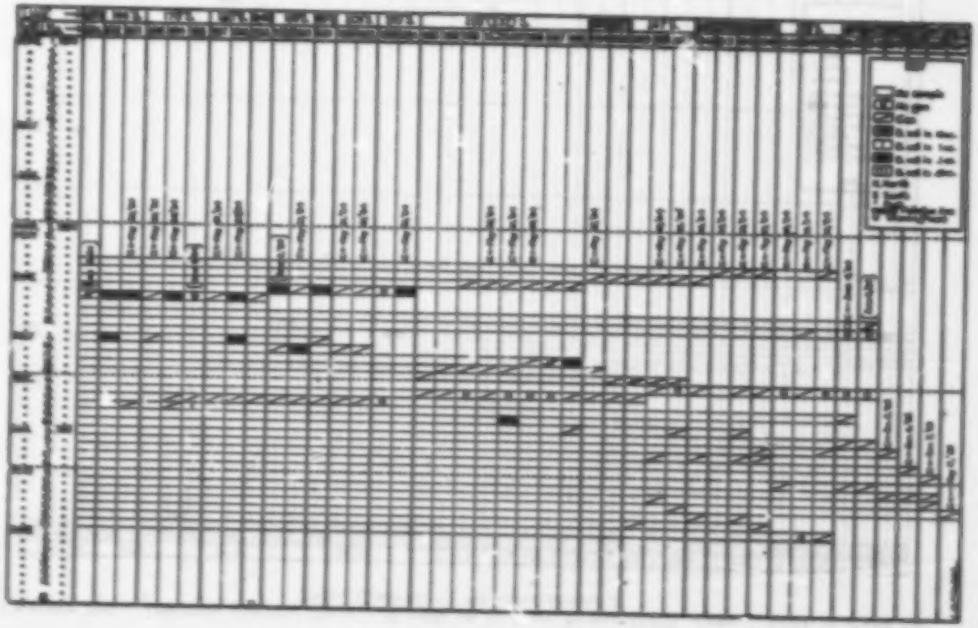


EXHIBIT 28c.—*Diagram showing log of 113 wells in 41 lines, Group 600B, June 1, 1933, to June 22, 1935, Controls C, Samples D and E*



From Exhibit 25 it is to be noticed that the uranin band gradually narrowed so that:—

On the 329-foot line it could be demonstrated only in a breadth of about 3½ feet;
On the 359-foot line it could be demonstrated in a breadth of about 11½ feet;
On the 424-foot line it could be demonstrated in a breadth of about 12 feet; and
On the 450-foot line it could be demonstrated in a breadth of 21 feet.

Thus the uranin had decreased in breadth from 25 feet at the trench to 3½ feet at 329 feet south of the trench; then as it neared the line of the ocean waves and high tide it broadened again to 21 feet (i. e., nearly its original breadth). The thought lies near that this broadening was probably due to high tides and the pounding of the surf, but naturally this point could not be demonstrated.

The final conclusion is that at the end of the experimental observations (June 22, 1925) uranin pollution had been recovered up to a distance of 450 feet south of the trench and that *B. coli* pollution had been recovered up to line 228 feet south of the trench at a point 232 feet diagonally distant from the nearest (SW) corner of the trench.

At what greater distance the pollution might have been recovered had it been possible to continue the frequent examinations of the field, or if the ground water had moved swiftly (say up to 100 or 400 feet per day) instead of slowly (less than 1 foot per day), is at present *sub judice.*

LATER EXTENSION OF POLLUTION IN GROUP 500B (AUGUST 22, 1923, TO JANUARY 15, 1925)

Because of the underlying ground-water fall, the 500B group was not so satisfactory as the 600B group (see p. 63) for a study of further extension of the pollution. Nevertheless, later examinations showed that uranin was still persistent both in the soil and the ground water on June 20, 1925, i. e., after a period of one year and eight months, and that uranin was recovered at a distance of 80 feet south of the trench and *B. coli* and uranin at a distance of 70 feet south of the trench in the ground water.

Exhibit 29.—*Summary of 500B by lines, June 1, 1923, to Jan. 15, 1925, Controls C, Samples D and E*

Total by lines	June 1, 1923, to Jan. 15, 1925					Controls C [1]	Samples D	B. coli first recovered
	Number of samples	Gas		B. coli				
		Absent	Present	Absent	Present (Samples E)			
3 feet south (5 wells)	5	1	4	5	0	1	4	(2)
9 feet south (4 wells)	4	3	1	4	0	(3)	4	(2)
12 feet south (6 wells)	6	3	3	6	0	1	5	(2)
15 feet south (6 wells)	6	5	1	6	0	--------	6	(2)
21 feet south (7 wells)	7	7	0	7	0	1	6	(2)
30 feet south (2 wells)	2	2	6	2	0	1	1	(2)
35 feet south (1 well)	1	1	0	1	0	1	0	(2)
40 feet south (9 wells)	15	6	9	15	0	7	8	(2)
45 feet south (2 wells)	2	1	1	2	0	2	0	(2)
50 feet south (9 wells)	16	2	14	14	2	13	1	(2)
70 feet south (1 well)	1	0		0	1	0	0	Jan. 15, 1925
80 feet south (1 well)	1	0	1	1	0	1		(4)
Total 12 lines (53 wells)	66	31	35	63	3	28	35	
Per cent	--------	--------	53	--------	4	--------	--------	

[1] Numerical values for this exhibit.
[2] See Exhibit 30.
[3] No Controls C for dates of this exhibit.
[4] No B. coli.

Exhibit 30.—*Summary of Group 500B, by wells, June 1, 1923, to January 15, 1925, Controls C, Samples D and E*

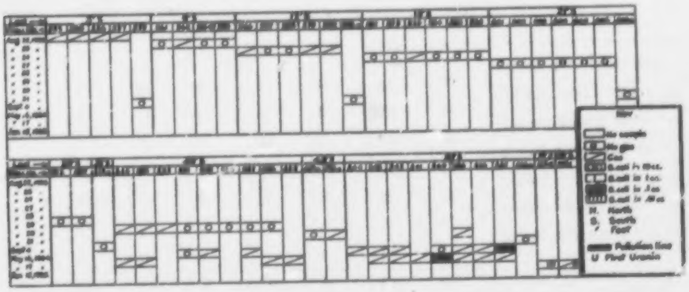
Distance from trench	Well No.	June 1, 1923 to Jan. 15, 1925					Controls C [1]	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
3 feet south	533	1	0	1	1	0	(3)	1
	535	1	0	1	1	0	--------	1
	536	1	0	1	1	0	--------	1
	537	1	0	1	1	0	--------	1
	539	1	1	0	1	0	1	0
Total	--------	5	1	4	5	0	1	4
9 feet south	561	1	1	0	1	0	--------	1
	562	1	0	1	1	0	--------	1
	564	1	1	0	1	0	--------	1
	581	1	1	0	1	0	--------	1
Total	--------	4	3	1	4	0	--------	4
12 feet south	566	1	0	1	1	0	--------	1
	567	1	1	0	1	0	--------	1
	568	1	1	0	1	0	--------	1
	570	1	0	1	1	0	--------	1
	582	1	0	1	1	0	--------	1
	583a	1	1	0	1	0	1	0
Total	--------	6	3	3	6	0	1	5
15 feet south	591	1	1	0	1	0	--------	1
	573	1	1	0	1	0	--------	1
	574	1	0	1	1	0	--------	1
	584	1	1	0	1	0	--------	1
	585	1	1	0	1	0	--------	1
	588	1	1	0	1	0	--------	1
Total	--------	6	5	1	6	0	--------	6

[1] Numerical values for this exhibit.
[3] No Controls C for dates of this exhibit.

Exhibit 30.—*Summary of Group 500B, by wells, June 1, 1923, to January 15, 1925, Controls C, Samples D and E*—Continued

Distance from trench	Well No.	June 1, 1923, to Jan. 15, 1925					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
25 feet south	801	1	1	0	1	0	--------	1
	802	1	1	0	1	0	--------	1
	803	1	1	0	1	0	--------	1
	804	1	1	0	1	0	--------	1
	805	1	1	0	1	0	--------	1
	806	1	1	0	1	0	--------	1
	806a	1	1	0	1	0	1	0
Total	--------	7	7	0	7	0	1	6
30 feet south	812	1	1	0	1	0	1	0
	807	1	1	0	1	0	--------	1
Total	--------	2	2	0	2	0	1	1
35 feet south	816a	1	1	0	1	0	1	0
40 feet south	834	2	0	2	2	0	2	0
	833	2	0	2	2	0	--------	2
	832	1	0	1	1	0	1	0
	831	2	2	0	2	0	2	0
	830	2	1	1	2	0	2	0
	828	1	1	0	1	0	--------	1
	827	2	1	1	2	0	--------	2
	826	2	1	1	2	0	--------	2
	825	1	0	1	1	0	--------	1
Total	--------	15	6	9	15	0	7	8
45 feet south	827a	1	1	0	1	0	1	0
	826a	1	0	1	1	0	1	0
Total	--------	2	1	1	2	0	2	0
60 feet south	844	1	0	1	1	0	1	0
	843	2	0	2	2	0	2	0
	842	2	0	2	2	0	2	0
	841	1	0	1	1	0	1	0
	840	2	1	1	1	1	1	0
	838	3	0	3	3	0	3	0
	836	2	0	2	2	0	2	0
	835	2	0	2	1	1	0	1
	835a	1	1	0	1	0	1	0
Total	--------	16	2	14	14	2	13	1
70 feet south	1060	1	0	1	0	1	0	0
80 feet south	1061	1	0	1	1	0	1	0

Exhibit 31.—*Diagram showing log of 53 wells in 12 lines of Group 500B, June 1, 1923, to January 15, 1925, Controls C, Samples D and E*



GROUP 900—CONTROLS C, SAMPLES D AND E

(Bacteriological determinations by Thomson)

This group contained 25 wells, Nos. 901 to 925.

Three pipes (900A, B, C), 1¼ inch, with well-strainer points, were driven into ground water; the top of the strainer was at elevation 8.12, the bottom of the strainer at elevation 7.37. A total of 25 ⅛-inch wells was driven in seven parallel lines. Pipes 900A, B, C, were dosed April 3, 1923 (under heavy pressure by force pump), each with 2½ quarts of uranin plus thin can-privy excreta which had been passed through a sieve to remove the larger particles. May 11, 1923, 2 quarts of additional material plus uranin were added to each pipe. In this way contamination was introduced into the ground water below the water table.

In all a total of 480 water samples was taken. Of these, 165 samples were taken prior to dosing, but not one of these showed *B. coli*.

Of the 480 samples, 66 showed gas, 19 were *B. coli* positive, as shown in Exhibit 33. From this table it is seen that only 2 wells showed *B. coli*, namely, well 911 once, well 910 in 18 samples. As well 910 showed both uranin and *B. coli*, the conclusion is obvious that at least the uranin came from the dosing; and as 23 wells were *B. coli* negative the conclusion seems justified that since the uranin and the excreta were both inserted into the pipes at the same time both the uranin and the *B. coli* recovered from well 910 came from the experimental material. Although uranin was not recovered from well 911 (4 feet west from well 910), no reason seems to be apparent which would show that the *B. coli* recovered from the near-by well 911 came from a source other than the experimental pollution.

The details of the lines and wells are seen in Exhibits 32 and 33, as follows:

EXHIBIT 32.—*Summary of Group 900 by lines*

	Mar. 1 to May 31, 1923							
	Number of samples	Gas		B. coli		Controls C	Samples D	B. coli first recovered
		Absent	Present	Absent	Present			
6 feet north (level with dosing well)	44	40	4	44	0	44	0	
8½ feet south (above dosing well 3 feet)	76	66	10	76	0	76	0	
4¾ feet south (below dosing well 3 feet)	68	66	2	68	0	68	0	
6 feet south (level with dosing well)	191	158	33	172	19	139	33	Apr. 16, 1923.
12½ feet south (above dosing well 3 feet)	31	23	8	31	0	31	0	
13¾ feet south (below dosing well 3 feet)	23	18	5	23	0	23	0	
15 feet south (level with dosing well)	47	43	4	47	0	47	0	
Total, 7 lines (25 wells)	480	414	66	461	19	428	33	
Per cent			14		4	89	7	

Exhibit 33.—*Summary of Group 900 by wells*

Distance from pollution pipes	Well No.	Mar. 1 to May 31, 1923					Controls C	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
6 feet north	902 901	22 22	19 21	3 1	22 22	0 0	22 22	0 0
Total	--------	44	40	4	44	0	44	0
3½ feet south	905 904 903	26 25 25	23 19 24	3 6 1	26 25 25	0 0 0	26 25 25	0 0 0
Total	--------	76	66	10	76	0	76	0
4¾ feet south	908 907 906	22 23 23	20 23 23	2 0 0	22 23 23	0 0 0	22 23 23	0 0 0
Total	--------	68	66	2	68	0	68	0
6 feet south	913 912 911 910 909	38 38 39 37 39	34 35 33 17 39	4 3 6 20 0	38 38 38 19 39	0 0 1 18 0	38 38 11 13 39	0 0 27 6 0
Total	--------	191	158	33	172	19	139	33
12½ feet south	917 916 915 914	7 8 7 9	7 5 7 4	0 3 0 5	7 8 7 9	0 0 0 0	7 8 7 9	0 0 0 0
Total	--------	31	23	8	31	0	31	0
13¾ feet south	920 919 918	7 7 9	7 7 4	0 0 5	7 7 9	0 0 0	7 7 9	0 0 0
Total	--------	23	18	5	23	0	23	0
15 feet south	925 924 923 922 921	9 9 10 11 8	9 9 9 8 8	0 0 1 3 0	9 9 10 11 8	0 0 0 0 0	9 9 10 11 8	0 0 0 0 0
Total	--------	47	43	4	47	0	47	0
Total, 25 wells (7 lines)	--------	480	414	66	461	19	428	33

LATER EXTENSION OF POLLUTION IN GROUP 900, JUNE 1 TO SEPTEMBER 4, 1923.

Of 99 samples taken in the period June 1 to September 4, 1923, only 3 (taken from 6 feet south) showed *B. coli.* Uranin had extended 13¾ feet south of the line of pollution pipes. The band of pollution in Group 900 was different from the bands in 500A, 500B, 600A, and 600B, in two important details, i. e., (1) it was not so broad, and (2) it was broken up into narrow (1 to 2 inches) subbands; accordingly the chances for collecting positives were enormously reduced.

EXHIBIT 34.—*Summary of Group 900 by lines, June 1 to September 4, 1923*

Total by lines	June 1 to Sept. 4, 1923					Controls C[1]	Samples D	B. coli first recovered
	Number of samples	Gas		B. coli				
		Absent	Present	Absent	Present (Samples E)			
6 feet north (level with dosing well)	3	3	0	3	0	3	0	No B. coli.
3½ feet south (above dosing well 3 feet)	24	24	0	24	0	24	0	Do.
4¾ feet south (below dosing well 3 feet)	15	15	0	15	0	15	0	Do.
6 feet south (level with dosing well)	40	37	3	37	3	24	13	See Exhibit 32.
12½ feet south (above dosing well 3 feet)	4	4	0	4	0	4	0	No B. coli.
13¾ feet south (below dosing well 3 feet)	3	3	0	3	0	3	0	Do.
15 feet south (level with dosing well)	10	10	0	10	0	10	0	Do.
Total, 7 lines (25 wells)	99	96	3	96		83	13	

[1] Numerical values for this exhibit.

EXHIBIT 35.—*Summary of Group 900, by wells, June 1 to September 4, 1923*

Distance from pollution pipes	Well No.	June 1 to Sept. 4, 1923					Controls C[1]	Samples D
		Number of samples	Gas		B. coli			
			Absent	Present	Absent	Present (Samples E)		
6 feet north	902	1	1	0	1	0	1	0
	901	2	2	0	2	0	2	0
Total		3	3	0	3	0	3	0
3½ feet south	905	9	9	0	9	0	9	0
	904	8	8	0	8	0	8	0
	903	7	7	0	7	0	7	0
Total		24	24	0	24	0	24	0
4¾ feet south	908	5	5	0	5	0	5	0
	907	5	5	0	5	0	5	0
	906	5	5	0	5	0	5	0
Total		15	15	0	15	0	15	0
6 feet south	913	8	8	0	8	0	8	0
	912	8	8	0	8	0	8	0
	911	8	8	0	8	0	(²)	8
	910	8	5	3	5	3		5
	909	8	8	0	8	0	8	0
Total		40	37	3	37	3	24	13
12½ feet south	917	1	1	0	1	0	1	0
	916	1	1	0	1	0	1	0
	915	1	1	0	1	0	1	0
	914	1	1	0	1	0	1	0
Total		4	4	0	4	0	4	0
13¾ feet south	920	1	1	0	1	0	1	0
	919	1	1	0	1	0	1	0
	918	1	1	0	1	0	1	0
Total		3	3	0	3	0	3	0
15 feet south	925	2	2	0	2	0	2	0
	924	2	2	0	2	0	2	0
	923	2	2	0	2	0	2	0
	922	2	2	0	2	0	2	0
	921	2	2	0	2	0	2	0
Total		10	10	0	10	0	10	0

[1] Numerical values for this exhibit.

[2] No Control C for dates of this exhibit.

FACTORS INFLUENCING THE SPREAD OF POLLUTION BY GROUND WATER

Prior to the Fort Caswell experiments we were open-mindedly prepared to find that pollution might radiate in the ground water in any direction—even upstream if the flow were sufficiently slow.

Several observations at Fort Caswell gradually combined to direct attention to the upper portion of the ground water, in a straight line with the ground-water flow, as probably the locality most likely to show pollution. These observations were three, in particular, namely,

(1) In Group 500A the pollution extended toward the south (in the direction of ground-water flow), but not toward the north (against the flow), to certain wells on the 1, 2, 2¾, and 3½ foot lines, and then seemed to stop, for all water samples from $3^5/_8$ to 45 feet were negative for *B. coli* and beyond 4 feet were negative for uranin. The water from certain wells near the trench was so intensely green because of the uranin that it seemed incredible that the green color could fade out so suddenly.

In order to trace the uranin, sand borings and excavations were made, and it was found that in the capillary fringe, above the water table, there was a blanket (or stratum) of uranin, approximately 2 inches thick, extending out 17 feet from the trench, and uranin finally appeared also in a well 7½ feet from the trench. Of several possible explanations, one was that the water table had fallen as a result of the dry weather, and that the uranin might have filtered out in the capillary fringe, aided possibly by capillarity with the upper evaporation through the sand. If this hypothesis were correct, the uranin had probably floated out rather superficially in the ground water.

(2) The wells near the trenches were first arranged in sets of three each and at different depths, and the point was noticed that while a shallow well might show pollution positive another well about 3 inches away but drawing water from a few inches deeper would be pollution negative.

(3) The 1¼-inch well pipes, such as those used in the 100, 200, and 300 groups, had been rejected in favor of smaller, ¼-inch pipes, which could be easily raised and lowered at will, thus giving samples from higher or from lower water levels as desired. Experience soon showed that it was especially from the higher water level, near or at the water table, that the positives were obtainable.

Combining these three observations, we later took samples chiefly from the higher water level, namely, at the top of the water table, and experience shows that it is with these samples that the progressive movement of the pollution (as in the 500B and 600B groups) could be traced.

In explanation of the presence of *B. coli* in the more elevated samples, two theoretical considerations naturally arise—

(*a*) Is it not probable that these bacteria find more optimum oxygen conditions near the capillary fringe, hence tend to congregate near the surface of the water table?

(*b*) Is it not possible that the evaporation of water through the soil, combined with constant labile—rather than stabile—capillarity, tends to draw the bacteria upward?

Whatever the immediate cause of the condition, a question seems to arise as to the value to be attached to Controls A and B in the Groups 100, 200, and 300. The wells in question draw water from various depths, hence ofttimes from depths below the water table; accordingly, are the numerous negatives of any special significance as premise to the conclusion that the water was in reality *B. coli* negative? Our own viewpoint is that we attach less weight to these Controls A and B than we do to Controls C. That the Controls A and B are without value is not to be admitted, for the water table rose and fell repeatedly and the well records show that some of the wells were occasionally "dry"; accordingly, some of the Controls A and B were doubtless from the water table and might accordingly contain bacteria which had not been filtered out by the sand during the fall of the water or which had flowed in at that level; further, four small pipette wells installed later in Group 300 failed to show *B. coli* when water-table samples were taken. Nevertheless, the impression has forced itself upon us that the Controls A and B of Groups 100, 200, and 300 are of less importance than was attached to them in the early part of the work.

On the other hand, Controls C, consisting of numerous *B. coli* negative samples in Groups 500, 500A, 600, and 600A, taken from the water table in a search for *B. coli*, are, to our minds, of distinctly greater value in our argument than are the Controls A and B of Groups 100, 200, and 300; and we are willing to discard entirely the Controls A and B from our argument and to base our case on the Controls C plus the uranin findings in the *B. coli* samples. With this attitude, however, is combined a distinct scepticism as to the value of negative *B. coli* results in samples taken at random depths from wells and sent to laboratories for examination, if they are interpreted as proof that a given well has not become polluted from a given pit located up stream in the line of the ground-water flow.

4. RECOVERY OF EXPERIMENTAL BACILLUS COLI FROM THE SOIL AT FORT CASWELL[1]

By C. W. Stiles and G. E. Thomson

It has been shown (p. 26) that both uranin and *B. coli* were found in the capillary fringe at a time when they were not found in the ground water. It is shown (p. 27) also that of 12 soil samples examined May 24, 1922, from 20 to 100 feet outside of the 500A and 500B groups all were *B. coli* negative.

As studies progressed the working hypothesis developed that: As the ground water falls the bacteria probably filter out into the capillary fringe and as this latter lowers they probably are left stranded in the soil; then if this latter becomes "bone dry" *B. coli* dies (see p. 126).

Obviously, it was desirable to test out this hypothesis by soil examination in the polluted plot and this was done in the 600B set.

Exhibit 37 shows the results of 292 soil examinations on various dates and at different levels, and Exhibit 36 summarizes the soil sample examinations on various lines irrespective of depth.

It will be noticed from Exhibit 36 that *B. coli* was recovered from the trench (0-foot line), and also from the 35-foot, 45-foot, 55-foot, 80-foot, 85-foot, 110-foot, and 115-foot (7) lines, in a total of 13 samples out of 292 samples taken from 27 lines.

Exhibit 36.—*Summary of Soil Samples from 600B by lines, May 20, 1924, to June 20, 1925*

Distance from trench lines	May 20, 1924 to June 20, 1925				
	Number of samples	Gas		B. coli	
		Absent	Present	Absent	Present
0 feet south (in trench)	16	0	16	12	4
5 feet south	2	0	2	2	0
15 feet south	5	0	5	5	0
35 feet south	31	1	30	30	1
45 feet south	32	0	32	30	2
50 feet south	5	0	5	5	0
55 feet south	20	0	20	19	1
60 feet south	28	0	28	28	0
65 feet south	6	0	6	6	0
70 feet south	8	0	8	8	0
75 feet south	14	0	14	14	0
80 feet south	8	0	8	7	1
85 feet south	11	0	11	9	2
90 feet south	5	0	5	5	0
95 feet south	7	0	7	7	0
100 feet south	5	0	5	5	0
110 feet south	6	0	6	5	1
115 feet south	6	0	6	5	1
247 feet south	8	0	8	8	0
280 feet south	7	0	7	7	0
289 feet south	8	0	8	8	0
300 feet south	9	0	9	9	0
329 feet south	10	0	10	10	0
339 feet south	11	0	11	11	0
349 feet south	9	0	9	9	0
359 feet south	9	0	9	9	0
41[illegible] feet south	6	0	6	6	0
Total, 27 lines	292	1	291	279	13

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[1] Division of work was as follows: Plans by Stiles and Thomson; samples taken by Thomson; cultures by Alexander, Baker, and Thomson; argument by Stiles and Thomson.

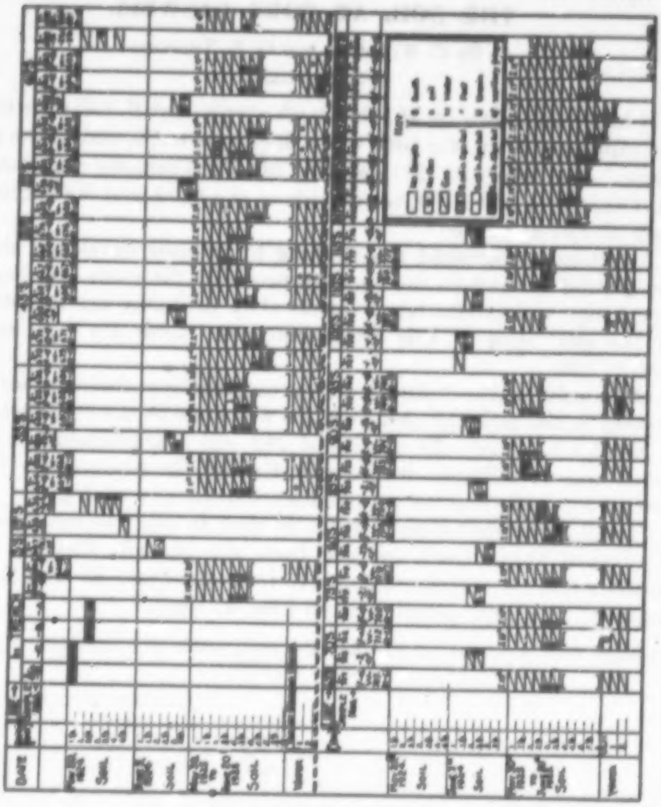

EXHIBIT 37.—*Diagram showing log of 222 soil samples at various depths (1 to 6 feet) and on 27 lines of 600B*

[In upper block, for 4½ read 6½]

It will also be noticed (Exhibit 37) that the positive uranin samples were recovered from the soil on lines: 0 foot (in trench), 3 feet, 15 feet, 35 feet, 45 feet, 55 feet, 60 feet, 70 feet, 75 feet, 80 feet, 85 feet, 90 feet, 100 feet, 110 feet, and 115 feet. Thus positive evidence is presented that on the fall of ground water uranin has filtered out into the soil.

These two last paragraphs show that both uranin and *B. coli* were recovered from the soil on lines 0 foot (trench), 35 feet, 45 feet, 55 feet, 80 feet, 85 feet, 110 feet, and 115 feet.

Both uranin and *B. coli* were found *in the same soil sample* for lines 0 foot and 115 feet.

A comparison of Exhibits 24 and 37 shows that the following *B. coli* positive soil samples were taken from immediately adjacent to the following wells *from which wells both uranin and B. coli* were recovered: Wells No. 658 (35-foot line), 673 (45-foot line), 684

(55-foot line), 694 (60-foot line), and 776 (115-foot line); further, *B. coli* positive soil samples were taken immediately adjacent to the following wells which showed uranin positive (we have no record of *B. coli* from these wells): Wells No. 726 (80-foot line), 733 (85-foot line), and 764 (110-foot line). Thus the proof is presented that material (*at least uranin*) from the trench had passed immediately adjacent to these soil samples, and since it has been impossible to find *B. coli* in the field except in the polluted (uranin) area the conclusion would appear justified that the *B. coli* also came from the trench.

Exhibit 38 shows also that the following positive samples were obtained at the levels (below the ground surface) stated:

EXHIBIT 38.—*Summary of* B. coli *and uranin soil samples in 600B*

Depth	B. coli only	B. coli+ uranin	Uranin only
1 to 4½ feet:			
1 foot			1
1½ feet	2	2	3
2 feet	1		6
2½ feet	3	2	6
3 feet			5
3½ feet	2		3
4 feet			1
4¼ feet			1
4½ feet	1		
Total	9	4	26

The distance from soil surface to ground-water table varied, as was to be expected. The level of the capillary fringe, with respect to ground level (soil surface) is shown in Exhibit 37 for some of the various lines for the two years (1924, 1925).

In summary it was possible to recover both *B. coli* and uranin from the soil (i. e., above the ground-water table) at various distances up to 115 feet south of the pollution trench 600B. Our interpretation is that both the *B. coli* and uranin pollutions were carried out on the higher ground water and were filtered out into the soil as the ground-water table fell.

5. URANIN TEST TO DEMONSTRATE POLLUTION OF WELLS

By C. W. Stiles, H. R. Crohurst, and G. E. Thomson

Of the various methods in use to demonstrate that material from a privy reaches a well or other water supply mention may be made of uranin and kerosene. In the Fort Caswell experiments uranin was used for this purpose; our (very few) tests with kerosene were incomplete.

The orange-red powder, "uranin," was first dissolved in water (the proportion is not essential) and the intensely green solution which resulted was poured into the trench and mixed with the excreta. When this green uranin water was later recovered in a given well the proof was obvious that material from the trench had reached the well; unless uranin was recovered from a given well or its immediate vicinity (one case, p. 76), the proof was not considered as absolutely (though possibly relatively) demonstrated that the well was polluted by material from the trench.

As proof of the presence of uranin in a given well, a very rigid standard was adopted, namely, *two or more persons familiar with the uranin test agreed that uranin was recognizable to the naked eye;* thus the pollution had to be well marked before it was accepted. In no instance was the conclusion in regard to uranin based upon examination with the fluoroscope. Had a fluoroscopic test been adopted, it is probable that our "positives" would have been increased and our "negatives" decreased in number. Accordingly, no ground seems to be present to question the "positives" or uranin findings.

During this study, several practical points developed in the test, some of which were new to us, though they may be known to other investigators. Of these the following in particular may be noted:

(1) If a uranin positive sample is exposed to a strong sunlight the green color may fade within a few hours or a day to such an extent that it can not be detected by the naked eye; accordingly, it is essential to protect the uranin sample from the action of strong sunlight.

(2) A uranin-positive sample of water can not be judged properly by artificial (electric) light; some water samples, which showed uranin positive during the day at the wells, would appear uranin negative in the laboratory during the evening when examined by electric light; but the next morning, under daylight, they appeared uranin positive.

(3) A water sample, which is clearly uranin positive when viewed against a background, such as sand, cloth, or clouds may appear uranin negative when held against the sun.

(4) A slightly to strongly cloudy water sample may appear uranin negative when first taken from the well; but if the sample is allowed to stand from a few minutes to a number of hours or days, to permit sedimentation, the cleared water may be strongly positive for uranin. Accordingly, judgment is to be reserved on cloudy samples until they have time to clear.

(5) Occasionally water samples were obtained which showed a faint slate-like tinge which could be easily mistaken for dilute uranin; but if these samples were allowed to settle the water became clear and the slate-like tinge settled with the sediment. This is directly opposite of what occurs in a uranin-positive sample, for the uranin becomes *more* distinct as the sediment settles.

(6) Although uranin can be distinguished in some soil samples (as in moist samples from the capillary fringe), it may be indistinguishable in other samples (as in dry sand), unless water is added and the sample allowed to settle. Accordingly, special caution is to be exercised in reading soil samples for uranin.

(7) In general, uranin pollution was found to travel more rapidly than *B. coli* pollution, but close to the point of original pollution exceptions to this general rule were occasionally met. On account of the (in general) more rapid travel of uranin, this substance seems to offer a practical forewarning of possible danger of later bacterial pollution.

In the *Wilmington experiments* uranin was used in only one pit (see p. 131).

In the *Fort Caswell experiments* uranin was used in the pollution pits 500A, 600A, 500B, 600B, and 900, and gave most satisfactory results: (1) In respect to its lasting qualities in the ground water (up to 31 months to date); (2) as an indication of the direction of the ground-water flow; (3) as an indication of the experimental source of ground water; and (4) as an indication of the pollution of the wells.

(1) *The lasting quality of uranin in ground water.*—Uranin was placed in the experimental trenches as follows:

In 500A on April 24, 1922.

In 500B on September 25 and 30, 1922; also on November 21, 1922, and April 3, 1923.

In 600A on May 10, 1922.

In 600B on October 11 and 17, 1922.

In 900 on April 3 and May 11, 1923.

The last observations, prior to the present writing, were in May and June, 1925, when the following data were obtained:

In 500A uranin was recovered from temporary wells in the trench on May 29, 1925. Thus it has persisted 3 years 1 month and 5 days.

In 500B uranin was recovered from the trench, both soil and water, on June 22, 1925. Thus it has persisted for a period of not less than 2 years 2 months and 19 days.

Soil samples which were examined June 22, 1925, and found strongly positive for uranin were again examined June 30, 1926, and the strong uranin still found present. The samples were kept in the laboratory under ordinary daylight and room temperature. These same soil samples, kept in the laboratory until May 17, 1927, still showed uranin on that date, namely, at the end of 4 years 1 month and 15 days.

In 600B uranin was recovered in wells on June 5, 1925. Thus it has persisted for at least 2 years 7 months and 19 days.

Accordingly, the present evidence is that when uranin is placed in a trench *and protected from the sunlight*, as it is in the ground and ground water, it can be recovered from the ground or from the ground water (i. e., wells) after periods of time varying from 2 years 2 months and 19 days up to 3 years 1 month and 5 days. These periods do not represent the actual *maxima* but simply the *maxima* of our present observations. From the present intensity of some of the samples we would fully expect to recover further uranin-positive sample months—possibly years—later (if we were able to continue the observations).

(2) *Uranin as an indication of direction of ground-water flow.*—By actual observations at low tide a discharge of ground water was observed on the beach to the south of the experimental field; this was in harmony with tentative deductions based upon the general contour of the land.

On the north of the experimental field is a pond which Doctor Stearns, of the ground-water division of the United States Geological Survey, as well as our staff, interpreted as the intake area of the ground water of the experimental field.

Accordingly, preliminary tentative interpretation was to the effect that the ground water was flowing in general from a northerly direction to a southerly direction, from the pond to the ocean.

The experimental trenches had surrounding wells of markedly close range (in some cases about 1 foot) both to the north and to the south. In not a single instance was uranin recovered in any well or in any soil of any line to the north of the trenches; on the other hand, the uranin was followed, somewhat diagonally, on the south side of the trenches, *gradatim* from trench to proximal wells, from proximal to distal wells, from distal to more distal wells, toward and to the ocean.

From these observations the conclusion is drawn that the ground-water flow through the trenches was, in general, in a southerly direction, not quite at right angles but slightly diagonally to the trench. Obviously, the uranin-green colored water went with the flow, not against it.

(3) *Uranin as an indication of the experimental source of ground water.*—As uranin was used only at certain places (trenches) in the experimental field, and as it is not found in nature, it is obvious

that the uranin recovered from any given well must have come from one of the pollution trenches; as there was uranin continuity in each plot (500, 600, and 900), but not between the plots, it is obvious that the uranin recovered from any given well came from the trench of the plot to which that well belonged and from no other source. The corollary of this is that the ground water containing that uranin had passed through the trench or immediately below it.

(4) *Uranin as an indication of the pollution of the wells.*—The immediate point at issue is to determine whether or not the experimental wells became polluted. All other questions, namely, whether or not uranin is poisonous; whether or not *Bacillus coli* is pathogenic; whether or not *Bacillus coli* is as satisfactory in a test as is *B. typhosus* or *B. dysenteriae;* whether or not it is legal, esthetic, refined, nauseating, conducive to health, dangerous, etc., to drink well water into which privies, hogpens, stables, manure piles, etc., have drained are for the moment to be omitted from consideration. The one and only question at issue and under consideration is: *Did the experimental wells become polluted or contaminated from the experimental trenches?*

The answer is—

(*a*) Since uranin is not found in nature;

(*b*) Since uranin was placed only in the trenches;

(*c*) Since uranin was not found in the wells to the north of the trenches;

(*d*) Since uranin was traced step by step from the proximal to the distal experimental wells on the south of the trenches; therefore—

(*e*) The north wells were not proved to be polluted from the trenches; but

(*f*) The south wells were demonstrated to be contaminated by at least one substance (uranin) from the trenches.

The details as to which wells in each line and experiment became contaminated from the trench. as proved by the presence of uranin in the well, are shown in the exhibits under the respective plots (500A, 500B, 600A, and 600B).

From these diagrams it is to be noticed that uranin has thus far been recovered in water samples up to a distance of 450 feet away from the pollution trench (600B).

In this connection it is important to consider that the water samples were obtained without excessive pumping. In fact, most of the water samples involved air-lift water samples of not over 100 cubic centimeters, and in very exceptional cases (as in excessive turbidity) did the pumping involve 1 liter of water. Thus, the present results are based upon a natural flow of the ground water—not an increased suction due to excessive pumping (which would doubtless have pronouncedly intensifying results).

6. VARIOUS FACTORS OF ENVIRONMENT TENDING TO DECREASE THE AMOUNT OF POLLUTION IN POLLUTED GROUND WATER

By C. W. Stiles and H. R. Crohurst

Summary.—Bacterial pollution of the ground water is subject to the influence of various environmental factors which tend to purify it. Among these factors may be mentioned: pH, drying due to fall of ground water in dry season, bacterial competition, protozoan competition, temperature, dilution of food supply, natural death rate of bacteria, and probably continued capillarity. As a result of this combination it is only natural to expect that a band of pollution as it floats out on the ground water will eventually be limited as to the distance it can extend. Were this not the case the ground water would contain all of the pollution which has reached it since the beginning of time and potable ground water (above an impervious layer) would be practically inconceivable.

If one considers only the *direction* of a polluted ground-water flow it is obvious that the *distance* to which the pollution can extend seems potentially to be practically unlimited. In this premise the conclusion would seem to be forced that the present ground water would contain all of the accumulated pollution that has reached the ground water since the beginning of time, and it is obvious that the present existence of a pure drinking water above an impervious stratum would be scarcely thinkable. The large number (7,644) of *B. coli* free water samples found in the Fort Caswell experiments (as well as general experience) demonstrates the fallacy of the foregoing conclusion. Accordingly, the extension of pollution must be limited by factors, some of which are not difficult to uncover.

Hydrogen ion.—The pH limits for *B. typhosus* are 3.8 or 5 to 8.7 (fide Cohen, 1922, J. B., p. 226) and for *B. coli* they are 5 to 8.1 (fide Cohen and Clark, 1919, J. B., p. 413). Accordingly, when the pollution is subjected to a pH outside of these limits the bacteria in question tend to die. The pH of the soil is therefore an important factor in purifying the ground water.

Drying.—That unspored bacteria require moisture in order to survive for any great length of time is an established fact. The experiment reported on page 126 for pit 52 is an illustration of this point. The sand had been experimentally infected with *B. coli;* during the heat of summer this sand had become very dry; as a result, *B. coli* died out.

As ground water falls, obviously not only the sand filter but also capillarity naturally come into play and as a result both uranin and bacteria near the ground-water table have a tendency to filter out and to remain in the capillary fringe. This result was clearly demonstrated in the 500A experiment (p. 22). If the ground water falls to a level which brings the capillary fringe down to a level below the plane on which the bacteria are filtered out, these bacteria find themselves in the aerated "intermediated layer" (p. 102) of the soil, and if the dry season (i. e., low ground water) persists sufficiently long it is obvious that unspored bacteria, like *B. coli* and *B. typhosus*, will eventually die out because of drying

Thus the conclusion seems justified that the falling of the ground water, due to dry weather, is an important factor in causing the purification of polluted ground water.

Assuming (independent of the element of pH) that a 3-foot broad band of pollution (Exhibits 39–40) is floating out at the ground-water table, fall of ground water would be followed by a decrease in the size of this band of pollution and the entire pollution in question might be destroyed if the dry seasons are sufficiently long or sufficiently frequent.

Bacterial competition.—The effect of the competition between various species of bacteria seems too well established to require discussion at this point. Accepting (on basis of the literature) bacterial competition (or antagonism) as an established fact, it is obvious that *B. typhosus* and *B. coli* would be subject to this competition in the ground water and that this would be an additional factor in the purification.

Protozoan competition.—Admitting, without argument, that the value of protozoa in the destruction of bacteria may have been given too great weight in the writings of some authors, the fact must be accepted as established beyond challenge that at least some species of rhizopods, of flagellates, and of ciliates do devour bacteria and that they are more or less continuously at work in feeding. Accordingly, there appears to be no escape from the admission that they come into consideration as one of the factors in purifying water of its bacterial content.

It seems to be usually assumed that protozoa are not found in the unexposed ground water. Our general experience is to the effect that protozoa are not numerous in underground water, but that they are not entirely absent. While it appears to us that they must be accepted as one of the factors in the purification of this water, the rôle they play appears (from present data) to be exceedingly secondary when compared with the drying, the pH and the bacterial competition (*seu* antagonism).

Temperature.—That temperature may be something of a factor in purification is predicated on the known fact that bacteria have their maxima, optima, and minima in respect to temperature. Too little is known in regard to the temperature of the ground water of our experimental field at different dates to warrant statements as to the effects of temperature upon the bacteria in question; but even considering the fact that the air temperature varied from winter to summer, data are not available which would seem to justify us in assuming that temperature has been a major factor.

Food supply.—As the pollution extends, the original (fecal) food supply eventually becomes diluted, and conceivably this fact may play a rôle in the death rate of the bacteria. Just how much of a rôle it played in the Fort Caswell experiments we are not prepared to conclude.

Natural death of bacteria.—While any organism which multiplies by fission can, in a certain sense, be conceived of as being potentially immortal, data are not at present available to justify the unqualified conviction that *B. typhosus* multiplies normally in the ground water. Nor do we know definitely and mathematically whether or to what extent *B. coli* multiplies in the ground water—although it is difficult to assume that it does not reproduce at least to some extent. A natural death rate appears to be a justified assumption in regard to *B. typhosus*, and the justification for a denial of a natural death rate for *B. coli* is not established.

Continued capillarity.—Even independent of the fall of ground water, the force of capillarity is always at work at the surface of the ground-water table. The thought lies near that this might continuously act toward the elimination of *B. coli* from the polluted band, but as the water table is subject to almost constant changes of level this point would not lend itself readily to field demonstration. The nearest approach to an experiment along these lines would be in the laboratory—which of course would depart from natural conditions.

Tropism.—In one of our experiments fecal material was placed into a barrel of water and allowed to ferment. From a study of samples taken at different depths below the surface and studied by Mr. Pfau, the point became evident that *B. coli* was more numerous near the surface and decreased toward the bottom of the barrel. The thought lies near that a tropism was effective, namely, that the bacteria sought the upper layers close to the more abundant oxygen supply, or at least that they lived longer in these upper layers.

Although *B. coli* is facultatively anaerobe and aerobe, it seems to be generally accepted biologically as an aerobe. On this accepted premise, *B. coli* in the barrel would naturally tend, by tropism, toward the greater oxygen supply. This same oxygen-tropism must of necessity be in constant play in the ground water, for it is an accepted fact that there is air circulation in the soil with exchange of air between the air strata above and those below the soil level.

On the foregoing premises it would indeed be difficult to argue against an oxygen-tropism which tends toward the movement of *B. coli* (in the ground water) up toward the ground-water table and from there possibly still further upward into at least the lower layers of the capillary fringe.

Accordingly, the thought lies near that oxygen-tropism is one of the important factors in purifying ground water.

7. LOCATION OF PITS, ETC., IN REFERENCE TO WATER SUPPLY AS INFLUENCED BY GROUND-WATER POLLUTION

By C. W. Stiles and H. R. Crohurst

In Contributions No. 1 (Report to the Surgeon General, United States Public Health Service) there were tabulated the laws and regulations of various States, counties, and cities bearing upon the factor of the distance of the privy, etc., from wells, other drinking-water supplies, buildings, streets, etc. The prescribed distances varied according to different factors, such as water-tight or nonwater-tight condition of the privy, cistern, etc., as illustrated by the following table:

6 feet.—*From* cesspool, sink, drain, privy, stable, swine pen, privy well *to* pond, stream, watercourse.—Mass.,[1] Brockton,[2] 1913.[3]

10 feet.—*From* water-tight compartment *to* cistern.—Wisc.,[1] 1917;[3] King,[2] 1916.[3]

15 feet.—*From* cesspool, privy, privy vault *to* well for domestic use.—New Jersey, Woodbury, 1911.

From privy *to* branch, drain, gutter.—North Carolina, Durham, 1914.

20 feet.—*From* cesspool, privy vault *to* drain, watercourse, banks of pond.—Massachusetts, Newton, 1915.

From drain (not water-tight) *to* source of water for domestic use, well.—Massachusetts, North Adams, 1912.

From sewer or sink drain (not water-tight) *to* spring, water supply for culinary use, well.—Massachusetts, Southbridge, 1906.

From tight cesspool *to* water-tight cistern.—Michigan, Sault Ste. Marie, 1916.

From privy vault *to* well.—Nebraska, Beatrice, 1918.

From privy vault *to* stream of flowing water, well.—New Jersey, Salem, 1915.

From water-tight compartment *to* spring, water supply for domestic purposes, well.—Wisconsin, 1917; King, 1917.

25 feet.—*From* cesspool, sink drain, swine pen, privy well, privy *to* well of owner.—Massachusetts, Brockton, 1913.

From cesspool, horse and cow stable, manure vault, privy vault *to* well for domestic use.—New Jersey, Hightstown, 1911, p. 9.

From nontight cesspool, reservoir into which water-closet, privy, sink, or stable is drained, privy vault *to* spring, water supply for drinking or culinary use, well.—New York, Oyster Bay, 1912, 1913, 1918.

From drainage system of LRS or septic privy *to* spring, water supply for domestic use, well.—North Carolina, 1919, p. 20.

From surface privy *to* natural drain.—North Carolina, Raleigh, 1912.

From water-tight privy vault *to* cistern, spring, water supply for drinking, well.—Wisconsin, 1917; King, 1916.

From nonwater-tight cesspool *to* spring, water supply for culinary or domestic use, well.—Massachusetts, Newton, 1915; Wakefield, 1910.

From tight cesspool *to* spring, water supply for drinking or culinary purposes, well.—Michigan, Sault Ste. Marie, 1916, p. 48; Ohio, Mansfield, 1912.

32.8 feet, i. e., 10 meters.—*From* cesspool *to* cistern, well.—Porto Rico, 1913.

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[1] State.

[2] County, city, or author.

[3] Date of publication of law, ordinance, regulation, or article.

33 feet.—*From* nonwater-tight cesspool *to* spring, water supply for drinking or ice, well.—Massachusetts, Clinton, 1914.

From cesspool, sink drain, swine pen, privy, privy vault *to* pond, stream, water course.—Massachusetts, Clinton, 1914.

From nonwater-tight cesspool, privy vault *to* spring, water supply for drinking purposes, well.—Massachusetts, Quincy, 1913, 1914.

From cesspool, water closet, sewer drain, privy *to* water supply for domestic use, well.—Massachusetts, Wakefield, 1910.

40 feet.—*From* cesspool, cow or horse stable, manure vault, privy vault, *to* well for domestic use.—New Jersey, Metuchen, 1901.

From nonwater-tight cesspool, privy *to* running brook, stream, tide-water, well.—New York, Freeport, 1916, p. 4.

From cesspool, privy, Imhoff tank, septic tank *to* well.—Florida, St. Augustine, 1916.

50 feet.—*From* every part of privy *to* spring or well for domestic use or drinking.—Alaska, Seward, 1912; District of Columbia, 1914.

From cesspool, manure pit, privy vault *to* spring, stream, well.—Connecticut, Greenwich, 1915.

From cesspool, reservoir into which water-closet, privy, or sink is drained; privy vault, *to* spring; water supply for drinking or culinary use; well.—Illinois, Blue Island, 1915; Geneseo, 1897; Harvard, 1916.

From water-tight cesspool, privy-vault *to* water supply for drinking or culinary use, well.—Iowa, Des Moines, 1912.

From cesspool, reservoir into which water-closet, privy, sink, stable, privy vault is drained *to* spring; water supply for drinking or culinary use; well.—Kansas, 1916, 1917.

From water-tight cesspool, privy vault *to* cistern, well.—Kansas, Hutchinson, 1912.

From privy, concrete privy vault *to* water supply for domestic use.—Kansas, Manhattan, 1917.

From cesspool, privy vault *to* water supply.—Manhattan, 1919.

From privy *to* well.—Louisiana, Alexandria, 1916.

From cesspool, sink drain, swine pen, privy, privy well *to* well, not owner's.—Massachusetts, Brockton, 1913.

From cesspool, privy vault *to* spring, water supply for culinary or drinking purposes, well.—Michigan, Holland, 1914.

From tight open-top cesspool, manure pit, reservoir used as a privy or receptacle for human or animal excreta, septic tank, privy vault *to* cistern, spring, water supply used for drinking or culinary purposes, well.—Michigan, Sault Ste. Marie, 1916.

From cesspool, privy vault *to* spring, stream, well.—New Jersey, Belleville, 1913.

From water-tight cesspool, manure pit, privy vault *to* stream, well for domestic use or otherwise.—New Jersey, New Brunswick, 1913.

From cesspool, manure pit, privy vault *to* spring, stream, well.—New Jersey, Nutley, 1914, p. 18.

From cesspool, privy vault *to* well.—New Jersey, Perth Amboy, 1913.

From water-tight cesspool, privy *to* stream, spring, well for drinking.—New Jersey, Princeton, 1916, p. 38.

From cesspool, manure pit, privy vault *to* stream of water, well for domestic purposes.—New Jersey, Rahway, 1909.

From cesspool, manure pit, privy vault *to* spring, stream, well.—New Jersey, Rutherford, 1909.

From catch basin, horse stable, manure vault, privy vault *to* well.—New Jersey, Salem, 1915.

Analysis of the foregoing data brings to the fore two very important points, namely:

(1) Existing laws, regulations, etc., have in mind the protection of the drinking water not only against pollution with human excreta (which might result in typhoid fever and bacillary dysentery) but also against filth in general (as from barnyard manure, etc.); but—

(2) Existing laws, regulations, etc., are predicated upon the factor of distance alone, *without reference to the direction of the flow of the ground water, except* in so far as this latter point might perhaps be implied in the references to streams.

On basis of the experiments at Fort Caswell, the point becomes obvious that distance alone is not the only factor to be considered.[4] Fundamentally, cases to be considered are to be divided into two major classes, namely:

A (B). *Locations when the direction of the ground-water flow is known,* and

B (A). *Locations when the direction of the ground-water flow is not known.*

A.—*Location of wells and pits when the direction of the ground water flow is known.*—It is to be noted that in the 500A, 500B, 600A, 600B, and 900 sets of experiments (see p. 6) the uranin and the *B. coli* pollution extended and was recovered in a southerly direction, namely, *in the direction of the flow of the ground water* and not in a northerly direction (against the flow of ground water); further, the findings did not give any ground for assuming that the pollution extended normally in a diffusing fan-like form (for exception, see p. 65); but, on the contrary, the findings showed that it progressed with nearly parallel, but converging sides which tended gradually into more or less of a longitudinal section of a truncated cone, i. e., trapezoid, with the polluted trench as base of the cone. (See, however, p. 65.)

This principle, that pollution extends in the direction of the ground-water flow and not in a contrary direction, is analogous to the principle that on an outflowing tide pollution from a sewer extends downstream (not upstream) in the river into which the sewer discharges.

On basis of this principle a well on the downstream side of a pit is in a much more dangerous location than one on the upstream side. Accordingly, a distance of 50 or x feet from the pit on the downstream radius of the circle formed with the pit as center point does not represent the same factor of safety as 50 or x feet on the other radii. This deduction is shown in Exhibit 39, where several theoretical bands of pollution are drawn, each band being predicated

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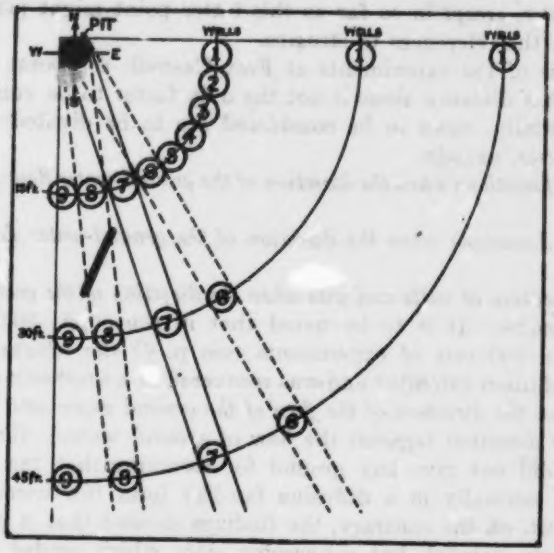
[4] This point is not unknown to sanitary engineers but does not appear to be emphasized in legislation.

upon the assumption that the flow is in the particular direction in question; one possible band is drawn as flowing south (9–9–9) from the privy to the well; any well in the path of this band is in danger, while a well on other radii, as north or east (1) or west, etc., would not normally be in danger.

EXHIBIT 39.—***Diagram of pit with 3-foot diameter, and some of the theoretical radii of pollution, with wells at 15, 30, and 45 feet away from the center of pit. A log of wood is inserted in radius 8, to deflect the flow of pollution***



It is, however, to be recalled that various factors may come into play to change or to deflect the direction of the ground-water flow from a given radius to some other radius. Two of these factors in particular are to be mentioned, namely, (*a*) *obstructions* and (*b*) *pumping.*

(*a*) *Obstructions.*—Obviously, it is impossible to foresee in all cases, or in fact generally, whether or not some obstruction, such as a geological tilt or a buried stone or tree stump or the tree trunk (see radii 7 and 8, Exhibit 39), might deflect the flow at a given point into a radius other than that in which a pollution might be flowing. In Exhibit 39, for instance, a log is inserted in one radius (8) and this log—if at the exact height of the theoretical band of pollution—would naturally deflect pollution from this radius into an adjacent line more or less parallel to the radius of assumed pollution. Accordingly, even in case of known direction of ground-water flow, exceptions to a theoretical diagram may occur. And in view of the

constantly changing level of the ground water, in nature, pollution might easily alternate between wells on adjacent radii according to the height of the ground water above, at the level of, or below the obstruction; it is even conceivable that when the ground-water level is just above the top or the bottom of the obstruction the pollution might be divided between two of the adjacent theoretical wells.

(*b*) *Pumping.*—Pumping is generally admitted as resulting in a cone-like effect in the water table immediately surrounding the well, the base of the cone being upward, the apex downward; and the base of the cone is generally admitted as varying in diameter in proportion to the depth of the well and the extent of the pumping.

In other words, *pumping changes temporarily the direction of the flow of ground water immediately adjacent to the well, with the well as the centripetal point of the altered flow; hence pollution in this ground water would be influenced temporarily in its flow by virtue of the pumping.*

B.—*Location of wells and pits when the direction of the ground-water flow is not known.*—In doubtless the majority of cases, when the location of a well or a pit is planned, the direction of the flow of the ground water is entirely unknown, probably not considered, or at best is assumed to be in the same direction as that of the surface drainage. Accordingly, the practical question arises as to the theoretical or mathematical chances of danger of pollution of a given well from a given privy or cesspool.

In order to reach a possible answer to this important question, let the conditions of soil (as sand) be assumed to be theoretically ideal, namely, of a thoroughly uniform composition (as sand) with uniform size of grains and interstices and with the grains sufficiently fine to render the deflection of water negligible; the ground-water flow is assumed to be uniform as to slope (or level) and rate.

Exhibit 39 is a diagram of a quadrant of a circle with the pit as center point. Let it be assumed that the direction of ground-water flow is unknown. The pit is assumed to be circular, 3 feet in diameter, and to be polluting the ground water in a band 3 feet broad—corresponding to the diameter of the privy.

If dug wells 3 feet in diameter are arranged on the 15-foot radius (under the regulations of Woodbury, N. J., 1911), there would be room [5] for approximately 31 (i. e., 31.4) wells. A band of pollution

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[5] The mathematical problem of the exact number of wells theoretically possible on a given periphery is of course complex and involves the question as to whether the center or the periphery or any intermediate point of the wells and of the privy is under consideration, the cutting of the periphery of adjacent wells, etc. For *approximate* estimate (not considering the question of overlapping) the following formula can be used:

r(radius = distance, center of privy to center of well) $\times 2\pi$ [$=6.2832$]
$\div d$(diameter of well and privy, say 3 feet). Thus
r [say 90 feet] $\times 2\pi$ [$=6.2832$] $= c$ [$=565.4880$ feet, circumference of circle]
$\div 3$ feet [= uniform diameter of privy and of well] $=188.496$ wells.

3 feet broad flowing from the pit in the direction x might coincide exactly with any one of 31 wells; or if the tangents of the pit and of the well did not coincide exactly the 3-foot blanket of pollution might strike two adjacent wells. Accordingly, the chances of the pollution reaching any given well located on the circle represented by a radius of 15 feet from the center of the privy would vary from ca. 6.67 to 3.33 per cent (ca. 1 in 15 to 1 in 31), and the chances that the pollution would not reach any given well in the circle would vary from ca. 93.33 to 96.67 per cent (ca. 14 in 15 to 30 in 31).

Extending this thought further, the chances of contamination in a circle of dug wells 3 feet in diameter at a distance x feet from the source of pollution expressed on a percentage basis can be represented by the following formula:

$$(a)\ \frac{47.75}{(x)} = \text{percentage contamination to}$$

$$(b)\ \frac{95.5}{(x)} = \text{percentage contamination.}$$

Formula (*a*) is applicable where the 3-foot band of contamination happens to coincide exactly with a well 3 feet in diameter and (*b*) where the band of contamination passes through parts of two adjacent wells.

Thus, under theoretically ideal and uniform conditions, the greater the distance of the well from the privy the greater are the chances that any given well will escape pollution, and at a distance of 100 feet the chances of contamination become less than 1 per cent. Obviously, therefore, the distance of the well from the privy is an exceedingly important factor in the chance safety of the well.

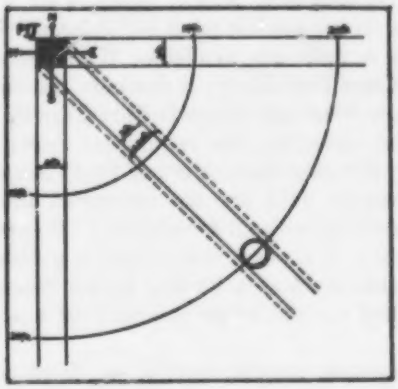
In nature, however, therefore in practical sanitation, theoretically ideal conditions can not be relied upon as being present. In cases of unknown direction of the flow of the ground water as in case of known direction of flow, the direction of the ground-water flow might be disturbed (*a*) by obstructions or (*b*) by pumping (see above, p. 94).

The shape of the pit is not without its influence on the mathematical chances of polluting wells. Most boards of health recommend or prescribe that the pit of a pit privy be square or oblong, but Georgia recommends a circular (Haygood) pit. Certain theoretical differences exist between the forms of these pits.

Exhibit 40 shows a circular (as a Haygood) pit projected on a square pit; the circular pit is assumed to be 3 feet in diameter; the other pit is assumed to be 3 feet square and facing north. If the ground-water flow is in any one of the four radii, north, east, south, and west, the theoretical band of pollution would be identical, namely, 3 feet broad from both the circular and the square pits.

If, however, the ground-water flow happens to be in any one of the four radii at 90°, namely, northeast, southeast, southwest, or northwest, the theoretical band of pollution would be 3 feet (= the diameter) in the case of the circular pit, but it would be 4.24 feet (an increase by about 40 per cent) in the case of the square pit, for it would correspond to the diagonal of the square pit, namely, the hypotenuse of the right-angle triangle represented by two sides of the pit.

Exhibit 40.—*Diagram of circular (3 feet diameter) and of 3 feet square pit showing varying breadth of theoretical pollution, according to direction of ground-water flow*



Carrying out this theoretical consideration further, it is seen that the theoretical band of pollution remains 3 feet in the case of the circular pit under consideration; but that there are four radii (north, east, south, and west) in which the theoretical band of pollution from the square pit under consideration would reach a minimum; and each deviation from north, south, east, or west toward the 90° angle (toward northeast, southeast, southwest, and northwest) involves a proportional increase in the breadth of the theoretical band of pollution until this reaches its maximum at the 90° radii, then toward the four radii (north, east, south, and west) the band decreases gradually to the minimum.

Accordingly, the circular pit, as recommended in Georgia on basis of an entirely different argument, has a theoretical advantage over square or oblong pits recommended by other boards of health.

The question of the gradual decrease of pollution in connection with the increase of distance from privy to well is discussed elsewhere. (See p. 88.)

8. INTERRELATION OF RAINFALL AND GROUND WATER AT FORT CASWELL[1]

By G. E. Thomson

Rainfall data.—Southport, N. C., about 4 or 5 miles from the experimental field, is the nearest point for which official United States Weather Bureau records are available; Wilmington, N. C., about 25 miles up the Cape Fear River, is the next nearest point. At the mouth of the Cape Fear and opposite Fort Caswell is Smith Island; according to local comment, the rainfall on Smith Island is much greater and more frequent than at either Fort Caswell or Southport; and although definite data are not accessible this popular belief seems to be not entirely without foundation. It appeared, therefore, that within a radius of about 5 miles there is a distinct variation in the rainfall; on this account a United States Weather Bureau rain gauge was installed on the experimental field near the 200 set of control wells.

The *average (normal) monthly rainfall* at Southport for a period of 45 years has been plotted on Exhibits 41–42 (cf. Exhibit 74); with this are plotted the monthly rainfall at—

(1) Southport in 1921;
(2) Southport in 1922;
(3) Southport in 1923;
(4) Fort Caswell (near the 200 set) in 1922; and
(5) Fort Caswell (near the 200 set) in 1923.

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[1] Rainfall readings at Southport are compiled from the United States Weather Bureau Reports. Rainfall readings at Fort Caswell were made by Crohurst, Jones, and Petrie. Record of ground-water elevations by Crohurst and Thomson. Final study and argument by Thomson. Manuscript submitted for criticism to Doctors Meinzer and Stearns, United States Geological Survey.

Exhibit 41.—*Graph of normal (average for 45 years) rainfall at Southport (plotted by months from Exhibit 74), with Southport, 1921) Southport, 1922, and Fort Caswell, 1922*

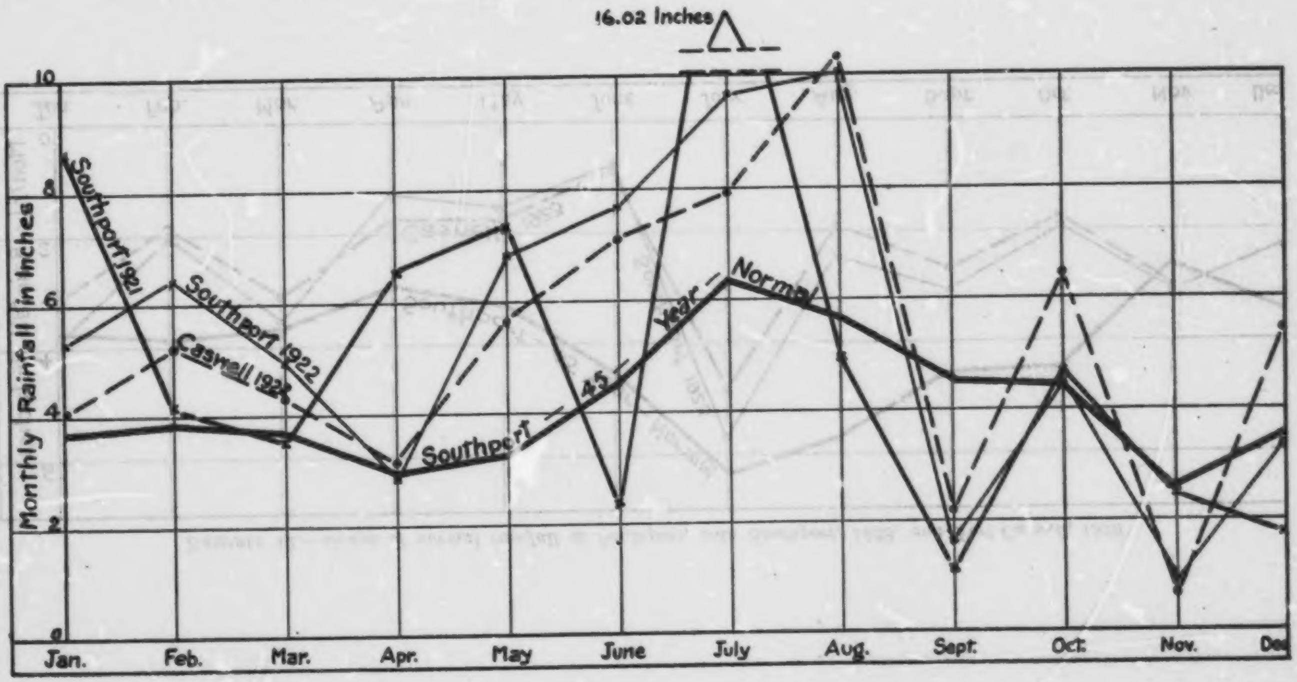


Exhibit 42.—*Graph of normal rainfall at Southport, with Southport, 1923, and Fort Caswell, 1923*

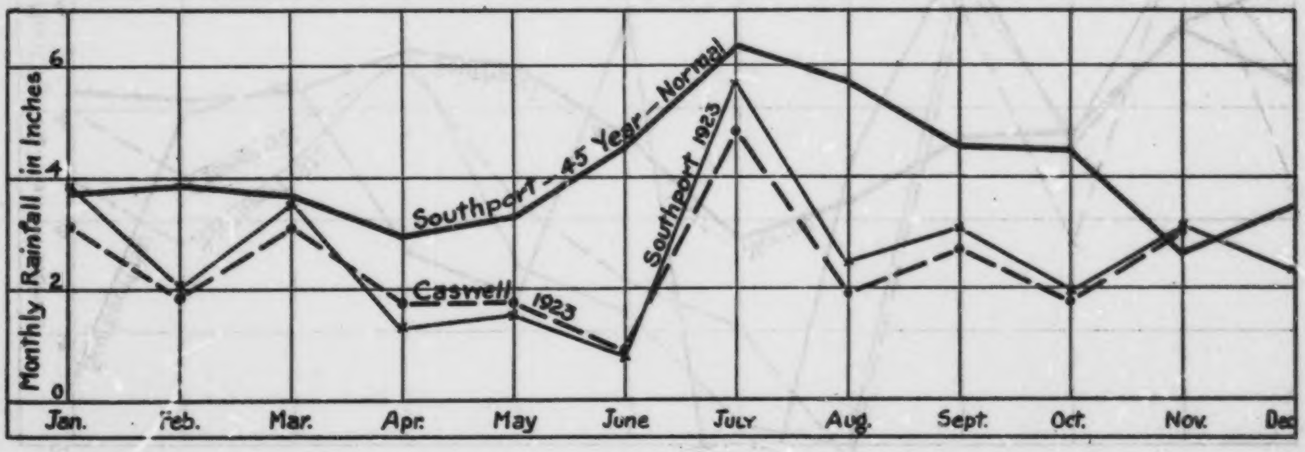
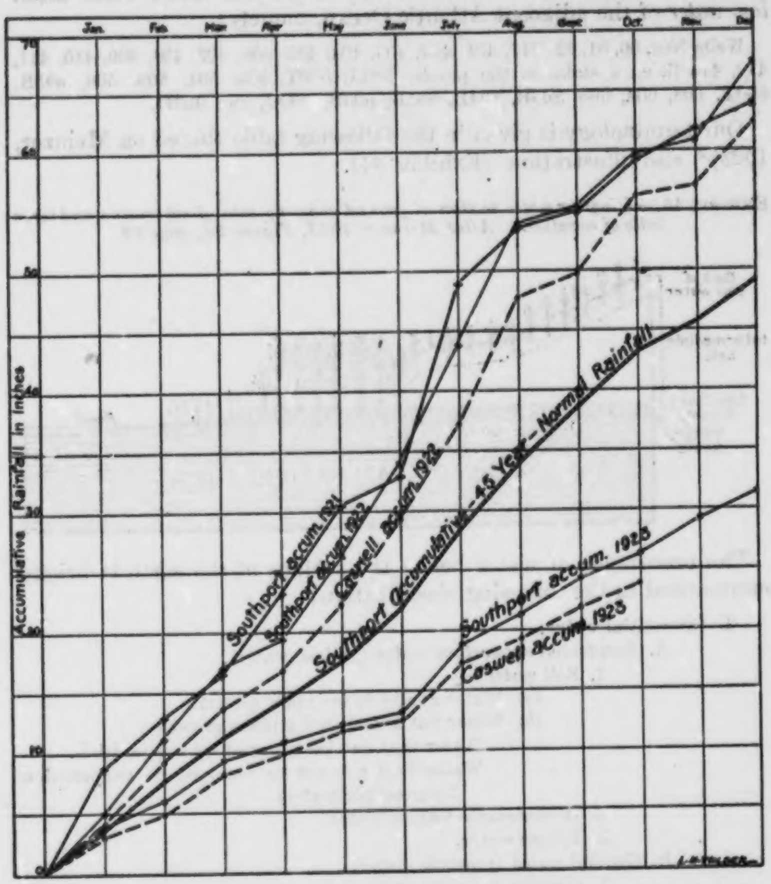


EXHIBIT 43.—*Graph of accumulative normal rainfall at Southport, with Southport, 1921, 1922, and 1923, and for Fort Caswell, 1922 and 1923*



The average *accumulative* monthly rainfall for Southport, on basis of the average for 45 years, is plotted on Exhibit 43; with this are plotted the accumulative rainfall for—

(6) 1922, at Southport;
(7) 1923, at Southport;
(8) 1922, near the 200 set; and
(9) 1923, near the 200 set.

From these data it is obvious that the rainfall for the experimental field during:

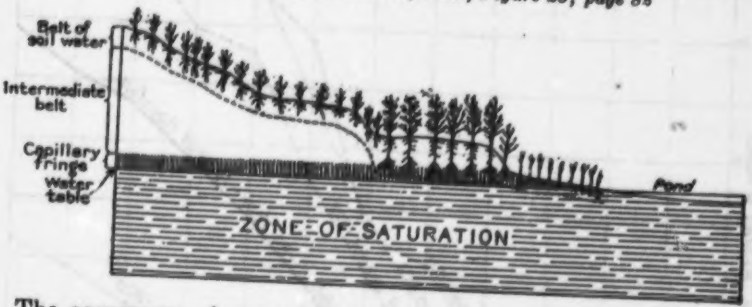
(*a*) 1922 was above the 45-year average at Southport; and
(*b*) 1923 was below the 45-year average at Southport.

Ground-water levels.—The following 34 observation wells (see Exhibit 1) were used to measure ground-water levels *above mean low water* of the adjacent Atlantic Ocean, namely:

Wells Nos. 60, 61, 62, 217, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413 (i. e., a stake in the pond), 500A, 500T, 503, 504, 505, 506, 595B, 600T, 603, 604, 605, 806B, 834B, 835B, 900B, 900C, and 900D.

Our terminology is given in the following table (based on Meinzer, 1923)[3] and illustration (Exhibit 44).

Exhibit 44.—*Diagrammatic section of ground showing zone of saturation and three belts of aeration. After Meinzer, 1923, Figure 29, page 88*



The occurrence of water below the surface of the earth is briefly summarized in the following classification:

- I. Interstitial water:
    - A. Suspended subsurface water (vadose water).
        - 1. Soil water —
            - (a) Water available for plant growth.
            - (b) Water not available for plant growth.
                - Water that can be removed by evaporation.
                - Water that can not be removed by evaporation (hygroscopic water).
        - 2. Intermediate vadose water.
        - 3. Fringe water.
    - B. Ground water (phreatic water).
        - 1. Gravity ground water.
        - 2. Ground water not under the control of gravity.
    - C. Subsurface ice (interstitial ice).
- II. Water in the mineral matter forming solid rocks (water in solid solution, water of crystallization, etc.).
- III. Internal water (and magmatic water above the zone of rock flowage).

In the present studies we were dealing with the capillary fringe and the saturated zone as shown in Exhibit 44 (A3 and B1 as shown in the summary key).

As the technique of measuring ground-water levels involved the theoretical constant risk of transferring contamination (if this were present) from one well to another, and as these wells were left open at the top in order to observe the water levels, these 34 wells were not utilized for water samples for bacteriological examination.

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[3] O. E. Meinzer, 1923, The Occurrence of Ground Water in the United States, with a discussion of principles. From Water-supply Paper 489, United States Geological Survey.

At first thought a study of ground-water levels in relation to rainfall may appear an exceedingly simple problem; that is, to measure the rainfall and at the same time, or a few hours later, the ground-water level. Experience shows, however, that the problem is much more complicated than it at first appears.

To take daily ground-water levels, in addition to our other work, would have required additional personnel which was not possible under our finances. Accordingly, daily data are not available, and we must be content with the less regular, though not insignificant, data which it was possible to collect.

Various factors operate to change ground-water levels, for instance, rainfall at intake area (the pond), outflow at discharge area (the beach), rainfall in transit through the aerated zone, evaporation through the capillary fringe or at points of temporary pools, temperature, and winds. The effect of pumping is to be ignored in the present studies, as unnecessary pumping was studiously avoided in order to obtain natural samples.

The 34 observation wells now under discussion can be divided into four groups, as follows:

EXHIBIT 45.—*Group 1: Observation wells.—Ground-water elevations on date of first observation from pond to beach, passing through area of Control Wells 200. Series continuous (i. e., observations from same wells, no new well put down), April 24, 1922, to May 31, 1923.*

Observation well No.	Elevation of ground above sea level (0.00)	Elevation of ground water above sea level (0.00)	Date of first observation	Remarks
	Feet	*Feet*		
413	15.11	13.98	Apr. 24, 1922	Stake in pond.
412	15.93	13.66	Apr. 19, 1922	
411	17.30	13.53	do	
410	18.22	13.43	do	
217	21.97	13.26	do	
401	17.11	12.43	do	
402	16.36	11.98	Apr. 18, 1922	
403	15.13	10.76	Apr. 19, 1922	
404	12.96	9.63	Apr. 18, 1922	
405	14.12	9.53	do	
406	15.06	8.77	do	
407	14.60	8.35	do	
408	12.62	7.63	Apr. 19, 1922	
409	11.62	6.87	do	

Total, 14.

Exhibit 46.—*Group 2: Ground-water elevations on date of first observation in 500A and 500B areas. Series (from April 24, 1922, to May 31, 1923) noncontinuous (i. e., old observation wells held until water failed, then new (deeper) wells were put down)*

Observation well No.	Elevation of ground above sea level (0.00)	Elevation of ground water above sea level (0.00)	Date of first observation	Remarks
	Feet	*Feet*		
504	12.93	9.66	Apr. 24, 1922	Governs 600B experiment also.
505	13.59	9.81	do	
503	11.30	7.61	do	
506	13.39	8.16	do	
505B	12.13	7.03	Apr. 21, 1923	
506B	12.04	7.80	do	
524B	12.23	7.0[illegible]	do	
525B	11.71	6.71	do	
500T	11.84	8.74	Nov. 21, 1922	In 500B trench.
500A	12.70	8.05	May 9, 1923	In 500A trench.

Total, 10.

Exhibit 47.—*Group 3: Ground-water elevations on date of first observation in 600A and 600B areas. Series (from April 24, 1922, to May 31, 1923) noncontinuous (i. e., old observation wells held until water failed, then new (deeper) wells were put down)*

Observation well No.	Elevation of ground above sea level (0.00)	Elevation of ground water above sea level (0.00)	Date of first observation	Remarks
	Feet	*Feet*		
504	12.93	9.66	Apr. 24, 1922	
604	20.05	11.90	Apr. 27, 1922	Taken up Mar. 3, 1923.
605	17.33	10.64	do	Governs 900 experiment also.
603	13.56	11.02	do	
600T	12.01	11.41	Oct. 11, 1922	In 600B trench.
60	12.51	10.20	Jan. 31, 1923	
61	11.26	9.61	do	
900D	13.80	10.25	Mar. 2, 1923	Governs 900 experiment also.
62	10.66	7.79	May 15, 1923	

Total, 9.

Exhibit 48.—*Group 4: Ground-water elevations on date of first observation in Group 900. Series (from March 2, 1923, to May 31, 1923) continuous*

Observation well No.	Elevation of ground above sea level (0.00)	Elevation of ground water above sea level (0.00)	Date of first observation	Remarks
	Feet	*Feet*		
605	17.33	[10.64	Apr. 27, 1922]	{This well was in before 900 experiment was started.
900B	16.37	10.45	Mar. 2, 1923	Mid-dosing well.
900D	13.80	10.25	do	Governs 600 experiment also.
900C	13.87	10.25	do	

Total, 4.

The foregoing data show that the experimental field was one of rather high ground-water level. In fact, on some dates the ground water was so high in certain portions of the field that small pools formed in depressions; but, in general, the ground water was about 2 to 6 feet below the ground surface.

The chief intake area is the pond at the up (north) side of the field; the chief discharge area is the beach. Other intake and discharge areas are more or less temporary, except areas of evaporation from the capillary fringe.

From the configuration of the land and the slope of the water table, the direction of the ground-water flow was expected to be from the pond to the ocean. Uranin experiments proved this inference to be correct, but that through our pollution areas the flow was slightly diagonal to the trench, as shown in Exhibit 21.

The available data consist of two comparisons, i. e., (*a*) *special cases* of rainfall readings correlated with special readings of ground-water levels shortly before a rain, and at the end of the rain, or shortly after the rain, and (*b*) *total accumulative monthly rainfall readings* correlated with average water level for the month (as based upon two or more readings) for the period April 24 to August 31, 1922.

a. The *special cases* can be summarized (arranged according to average rise) as follows:

EXHIBIT 49.—*Summary of Exhibits 50 to 54, showing rise of water levels in wells after rains*

Case No. (see Exhibit No.)	Time interval		Rainfall	Average rise
	Reading before rain	Reading after rain		
			Inches	*Inches*
III (52)	7 hours	5 hours	3.25	10.88
IIIa (53)	do	1 day	3.25	9.91
II (51)	1½ days	5 hours	2.12	6.77
I (50)	2 days	2 days	1.12	2.41
IV (54)	do	1 day	2.80	6.68

The following exhibits (50 to 54) show a series of (9 to) 12 shallow wells with depths ranging from 3.40 to 22 feet. The pond represents the first (No. 413) of the series; the wells are located in the order arranged in the Exhibits 1 and 51–54 in an approximately straight line (a distance of about 1,275 feet) from the intake area to the discharge area.

It is evident that after the rainfalls there has been a decided rise in the water levels.

Exhibit 50.—*Case I: April 27 to May 1, 1922*

Observation well No.	Depth of well	Ground-water level above sea level		Amount of rise
		Apr. 27, 2 days before rain of 1.19 inches	May 1, 2 days after rain of 1.12 inches	
	Feet	*Feet*	*Feet*	*Feet*
413 (pond)		13.91	14.01	0.10
412	4.00	12.50	12.71	.21
411	5.60	13.37	13.58	.21
410	6.35	13.24	13.42	.18
217	22.00	12.11	12.25	.14
401	7.45	12.27	12.35	.08
402	6.05	11.23	11.32	.09
403	4.90	10.53	10.69	.16
404	3.40	10.08	10.30	.22
405	5.15	9.28	9.62	.34
406	6.45	7.37	7.72	.35
409	6.60	6.74	7.07	.33

Twelve wells. Total rise, 2.41 feet; average rise, 0.20 feet.

Exhibit 51.—*Case II: May 15 to May 17, 1922*

Observation well No.	Depth of well	Ground-water level		Amount of rise
		May 15, 1½ days before rain of 2.12 inches	May 17, 5 hours after rain of 2.12 inches	
	Feet	*Feet*	*Feet*	*Feet*
413 (pond)		13.81	14.06	0.25
412	4.00	13.44	14.47	1.03
411	5.60	13.24	14.01	.77
410	6.35	13.07	13.40	.33
217	22.00	12.43	13.12	.69
401	7.45	12.13	12.31	.18
402	6.05	10.98	11.16	.18
403	4.90	10.31	10.78	.47
404	3.40	9.89	10.64	.75
405	5.15	9.10	10.06	.96
406	6.45	7.53	8.07	.54
409	6.60	7.02	7.64	.62

Twelve wells. Total rise, 6.77 feet; average rise, 0.56 foot.

Exhibit 52.—*Case III: June 19 to June 20, 1922*

Observation well No.	Depth of well	Ground-water level		Amount of rise
		June 19, 7 hours before rain of 3.25 inches	June 20, 5 hours after rain of 3.25 inches	
	Feet	*Feet*	*Feet*	*Feet*
413 (pond)		13.94	14.30	0.36
412	4.00	13.88	14.48	.60
411	5.60	13.59	14.71	1.12
410	6.35	13.40	14.28	.88
217	22.00	13.29	13.83	.54
401	7.45	12.67	13.30	.63
402	6.05	11.62	12.34	.72
403	4.90	11.05	12.04	.99
404	3.40	10.66	11.82	1.16
405	5.15	9.77	10.97	1.20
406	6.45	7.62	8.79	1.17
409	6.60	6.86	8.07	1.21

Twelve wells. Total rise, 10.58 feet; average rise, 0.88 foot.

EXHIBIT 53.—*Case IIIa: June 19 to June 21, 1922*

Observation well No.	Depth of well	Ground-water level June 19, 7 hours before rain of 3.25 inches	Ground-water level June 21, 1 day after rain of 3.25 inches	Amount of rise
	Feet	*Feet*	*Feet*	*Feet*
413 (pond)		13.94	14.21	0.27
412	4.00	13.88	14.37	.49
411	5.60	13.59	14.29	.70
410	6.35	13.40	14.19	.79
217	22.00	13.29	14.01	.72
401	7.45	12.57	13.51	.94
402	6.05	11.62	12.66	1.04
403	4.90	11.05	12.05	1.00
404	3.40	10.66	11.57	.91
405	5.15	9.77	10.82	1.05
408	6.45	7.62	8.73	1.11
409	6.60	6.86	7.75	.89

Twelve wells. Total rise, 9.91 feet; average rise, 0.82 foot.

EXHIBIT 54.—*Case IV: August 25 to August 29, 1922*[1]

Observation well No.	Depth of well	Ground-water level Aug. 25, 2 days before rain of 3.80 inches	Ground-water level Aug. 29, 1 day after rain of 3.80 inches	Amount of rise
	Feet	*Feet*	*Feet*	*Foot*
413 (pond)		14.21	14.41	0.20
412	4.00	14.05	14.50	.45
411	5.60	14.20	14.67	.47
410	6.35	14.33	14.93	.60
217	22.00	14.30	14.97	.67
401	7.45	13.71	14.47	.76
402	6.05	12.78	13.43	.65
404	3.40	11.56	12.08	.52
405	5.15	10.82	11.48	.66

[1] Readings not available for wells Nos. 403, 408, and 409.

Nine wells. Total rise, 4.98 feet; average rise, 0.55 foot.

b. Averages.—If, instead of special observations, averages per month based upon a small number of observations are taken, the correlations obtained between rainfall and water levels will be influenced by the chance of a water-level reading at time of high or low ground water. The data available for 15 observation wells[2] with rainfall from April 24 to August 31, 1922, are shown in detail on Exhibit 55 and in summary for 13 of the observation wells on Exhibit 56. Exhibit 57 gives a cross section of the field through observation wells 409 to 413, running south-north. It shows the land surface and the water table on three of the dates, May 1, May 31, and June 20, 1922. Exhibit 55 shows a very perceptible rise in general in the water levels of the wells soon after each rain. Exhibit 56 shows that in the majority of the wells *the trend of the ground water is upward as the rainfall is on the increase.* The fact here seems to be that in 1922 there was a progressive increase in the monthly rainfall from April to August, inclusive, and, with a few exceptions, a resultant progressive rise in the water level in the observation wells. This progressive rise is the more impressive because it occurred during the summer months when discharge by evaporation is at its maximum and when water levels in wells are, consequently, generally on the decline.

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[2] In Group 1 of foregoing series of observation wells, p. 103, with the exception of well 504, which is in Group 3.

The elevations of well No. 504 (of Group 2 and Group 3) have been plotted in both the detailed graph (Exhibit 55) and the summary graph (Exhibit 56) to show the consistent rise in the ground-water level after rainfalls during the same period.

From September 1, 1922, to May 31, 1923, the data are limited to few readings. The period showed a gradual lowering of the water table until many of the wells became dry. In some of the groups (those close to and governing the experimental plots) new observation wells were sunk at greater depths in order that the trend of the water level could be followed for practical deductions. If the decline of the ground-water level from August 31, 1922, to May 31, 1923, be compared with the rainfall for the same period the fact is outstanding that *the level of the ground water declined as the rainfall for the period diminished* (see rainfall decline August–December, Caswell, 1922, Exhibit 41; January–May, Caswell, 1923, Exhibit 42).

There is the contrast between the case in which the rise was recorded 5 hours after the rain (Case III) and then again 19 hours after the five-hour recording (Case IIIa). From graphs of Case III and of Case IIIa, there were seen the sharp curves of the 5-hour period changed to fairly sharp curves of the one-day period. When the values of the two were compared it was found that during the interval from the five-hour period to 19 hours later the water levels had fallen an average of 0.67 inch. (See Exhibit 49.)

Relative normal profile.—A very important profile of a water table is one which shows it in a quiescent condition after a long period without rain. Such a profile compared with profiles made soon after rain gives the effect of the rainfall on the water table.

Four profiles (of *instances*), considered nearest normal (i. e., longest periods obtainable after rainfalls), were made from data not cited in the foregoing (all premises being identical, however—same wells, same number of wells; etc.). These are here designated "relative normal profiles." Exhibit 58 gives a comparison (as respects the periods after rain and the amount of rain) between the profiles of the cases and the profiles of the instances.

From the average of these four *instances* (see Exhibit 59) one profile, "the normal profile" (see Exhibit 60) has been obtained with which to compare the profiles of the five *cases*.

Exhibit 55a.—*Detailed graph of rainfall and of ground-water table elevations of 15 observation wells*

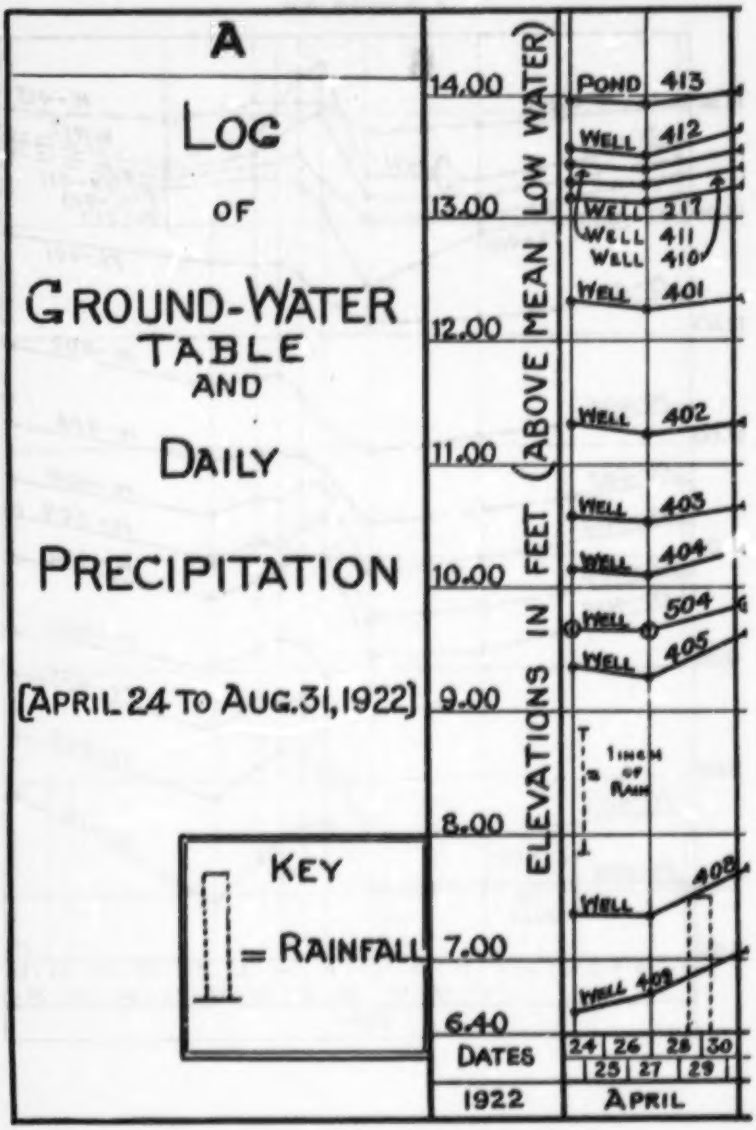


Exhibit 55b.—*Detailed graph of rainfall and of ground-water table elevations of 15 observation wells*

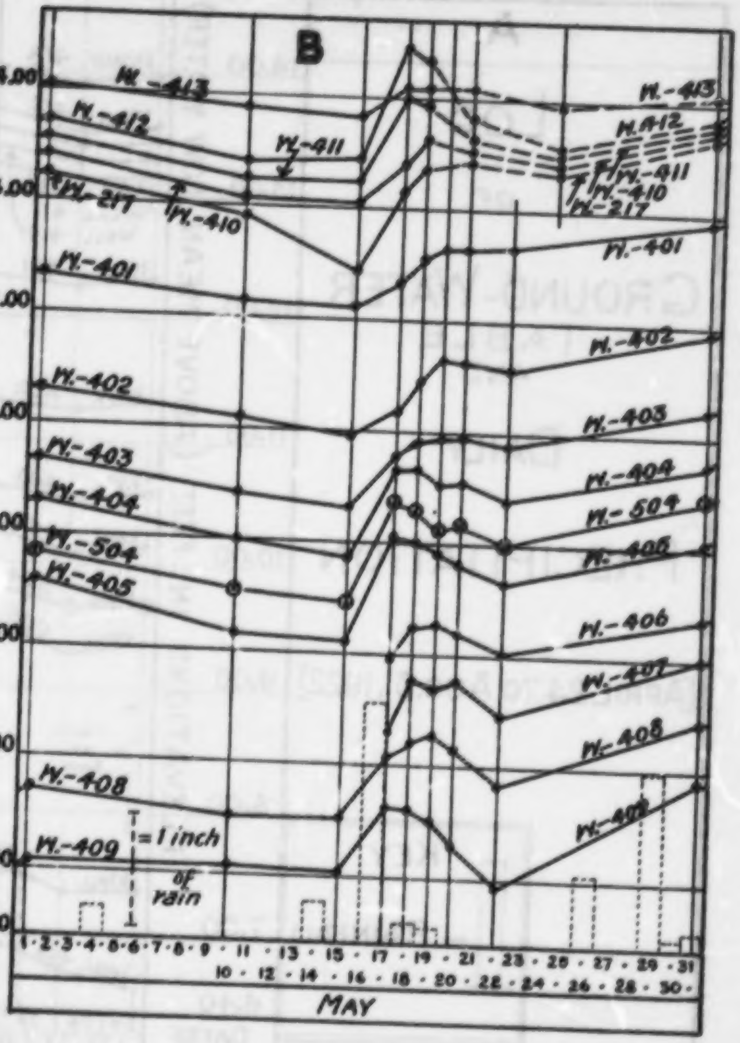


EXHIBIT 55c.—*Detailed graph of rainfall and of ground-water table elevations of 16 observation wells*

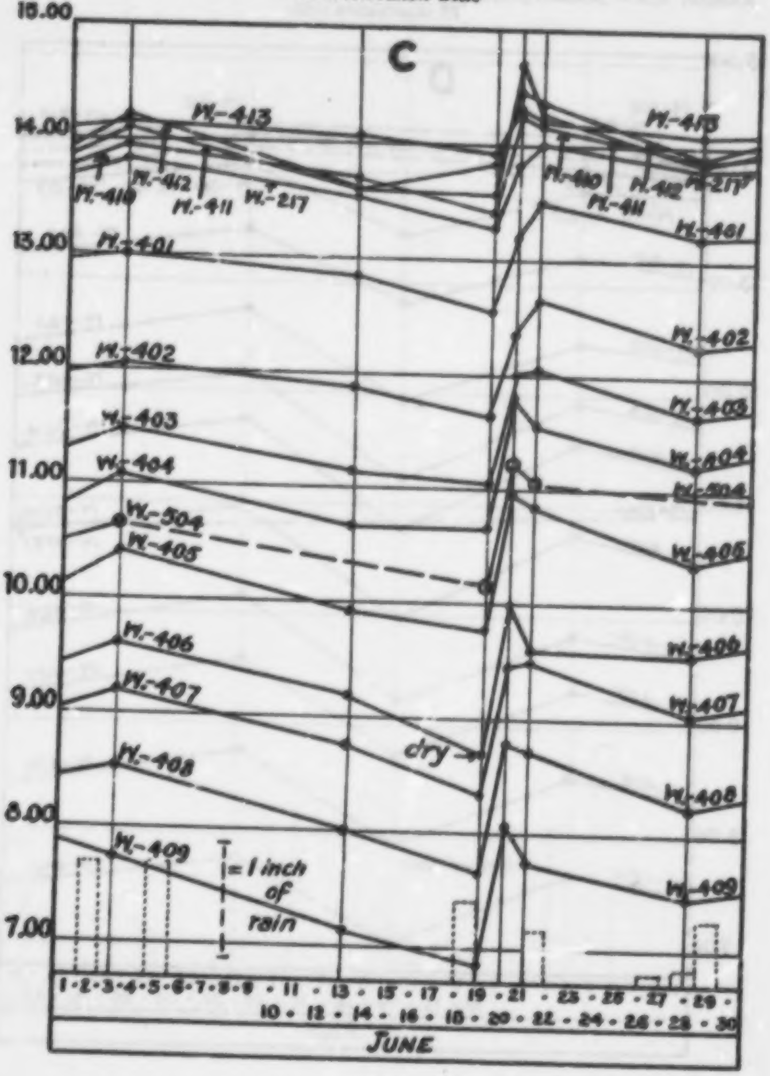


Exhibit 55d.—*Detailed graph of rainfall and of ground-water table elevations of 15 observation wells*

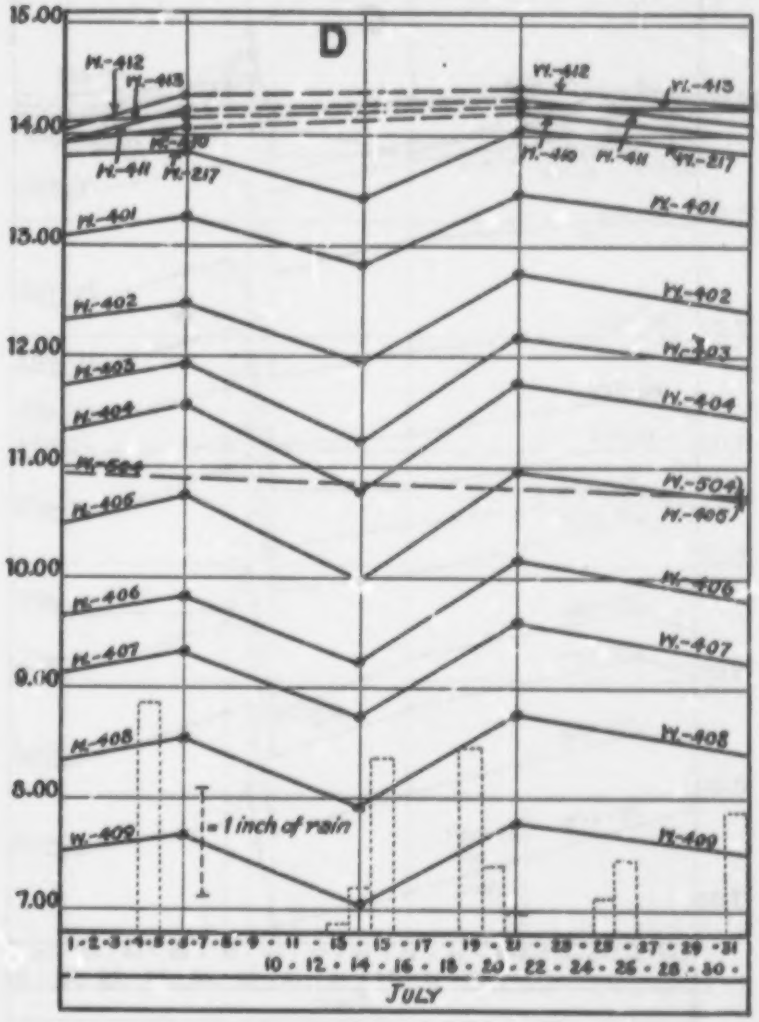


Exhibit 55e.—*Detailed graph of rainfall and of ground-water table elevations of 15 observation wells*

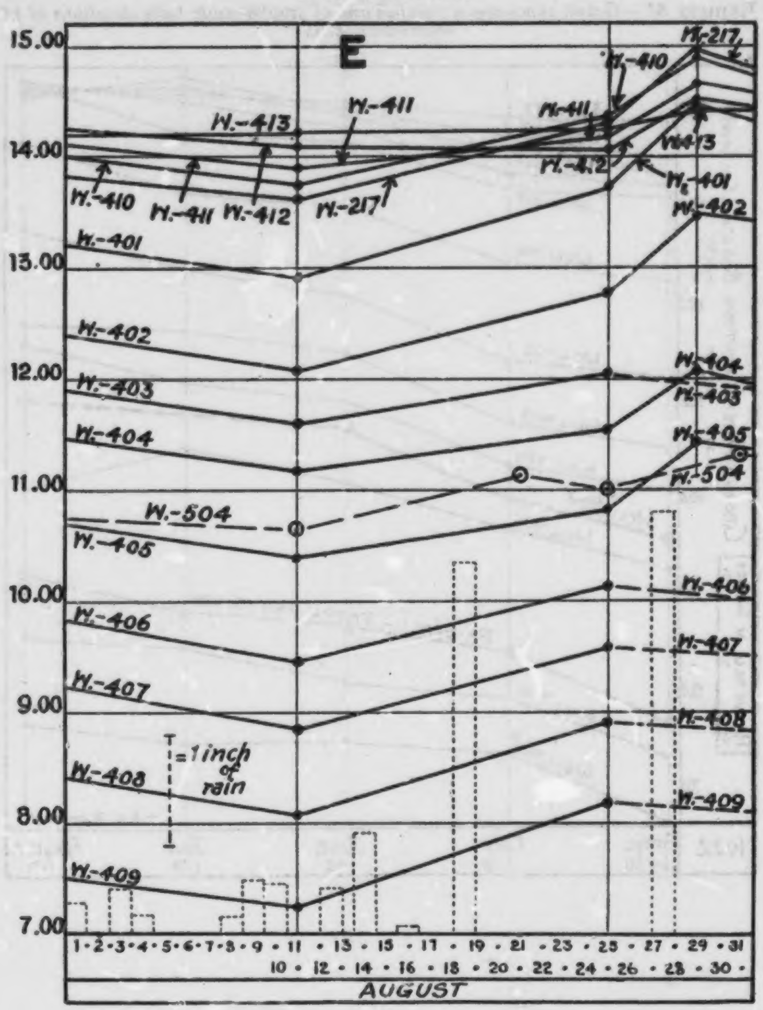


Exhibit 56.—*Graph summary of rainfall and of ground-water table elevations of 13 observation wells*

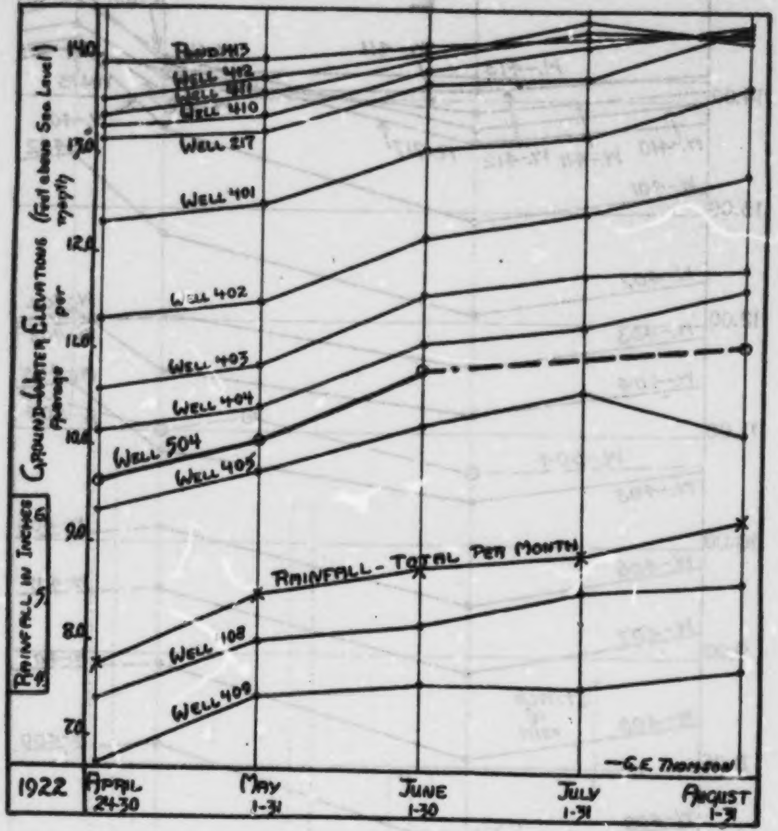
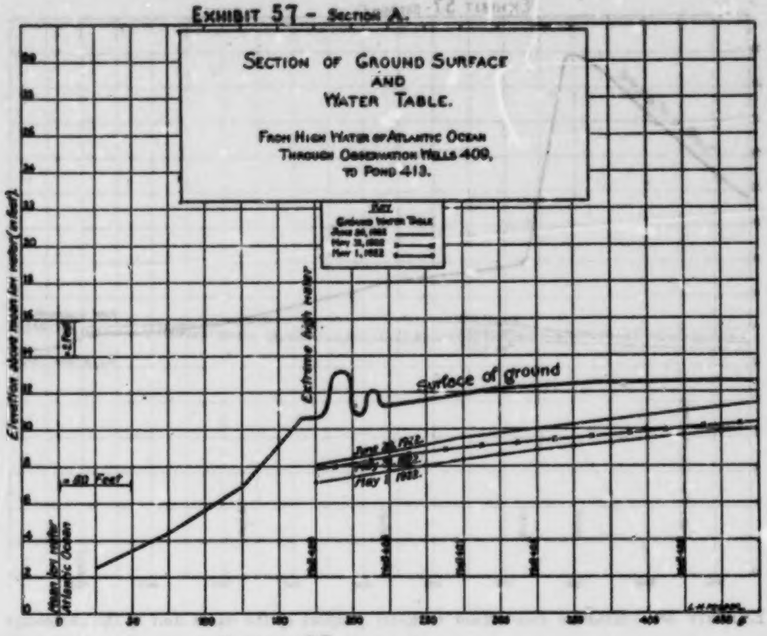


Exhibit 57.—*Section of ground surface and of water table, May 1 and 31 and June 20, 1922 (south to north, wells 409 to 413, pond)*



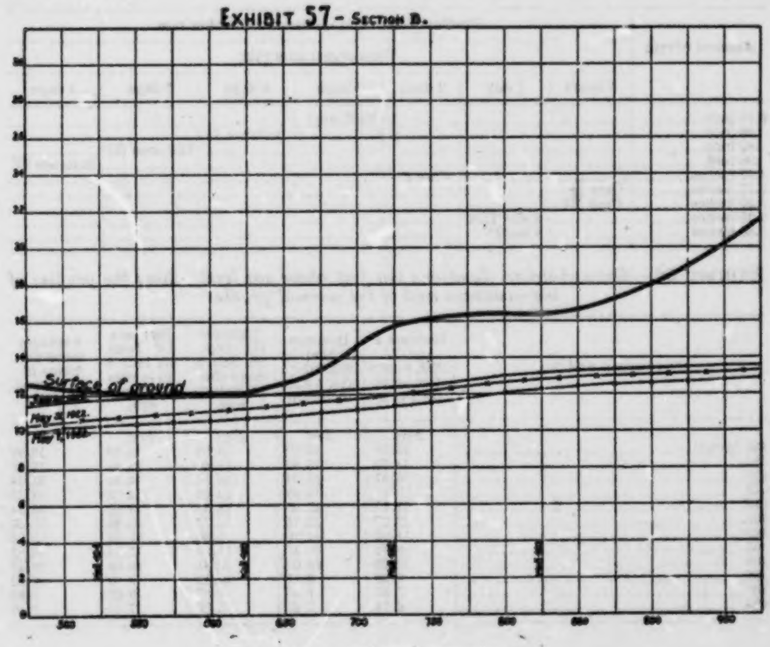


Exhibit 57.—*Section of ground surface and of water table, May 1 and 31 and June 20, 1922 (south to north, wells 409 to 413, pond)*—Continued

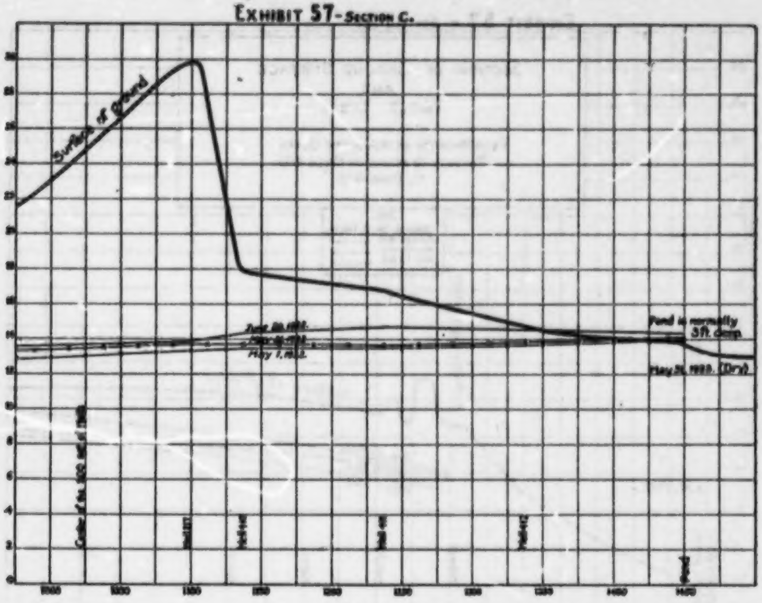


Exhibit 58.—*Relative connection between profiles of the cases and of the instances*

Amount of rain	Profiles of cases and instances made after rain						
	Time period after rain						
	5 hours	1 day	2 days	5 days	6 days	7 days	8 days
0.16 inch				Instance I			
.28 inch					Instance II		
.42 inch						Instance III	
.98 inch							Instance IV
1.12 inches			Case I				
2.12 inches	Case II						
3.25 inches	Case III						
3.25 inches		Case IIIa					
3.80 inches		Case IV					

Exhibit 59.—*Ground-water elevations (in feet above sea level) along the profiles of the instances and of the normal profile*

Observation well No.	Instance I: Apr. 27, 1922, 5 days after a 0.16-inch rain	Instance II: May 10, 1922, 6 days after a 0.28-inch rain	Instance III: Sept. 28, 1922, 7 days after a 0.42-inch rain	Instance IV: June 13, 1922, 8 days after a 0.98-inch rain	Averages (determinants of the normal profile)
	Feet	*Feet*	*Feet*	*Feet*	*Feet*
413 (pond)	13.91	13.90	14.04	14.03	13.97
412	13.50	13.41	13.60	13.61	13.53
411	13.37	13.24	13.53	13.61	13.44
410	13.24	13.06	13.44	13.63	13.35
217	13.11	12.95	13.36	13.55	13.24
401	12.27	12.15	12.73	12.86	12.50
402	11.23	11.10	11.86	11.89	11.52
403	10.53	10.41	11.25	11.15	10.83
404	10.08	10.00	10.81	10.66	10.39
405	9.28	9.17	10.12	9.92	9.62
408	7.37	7.55	8.57	8.02	7.88
409	6.74	7.07	7.77	7.17	7.19

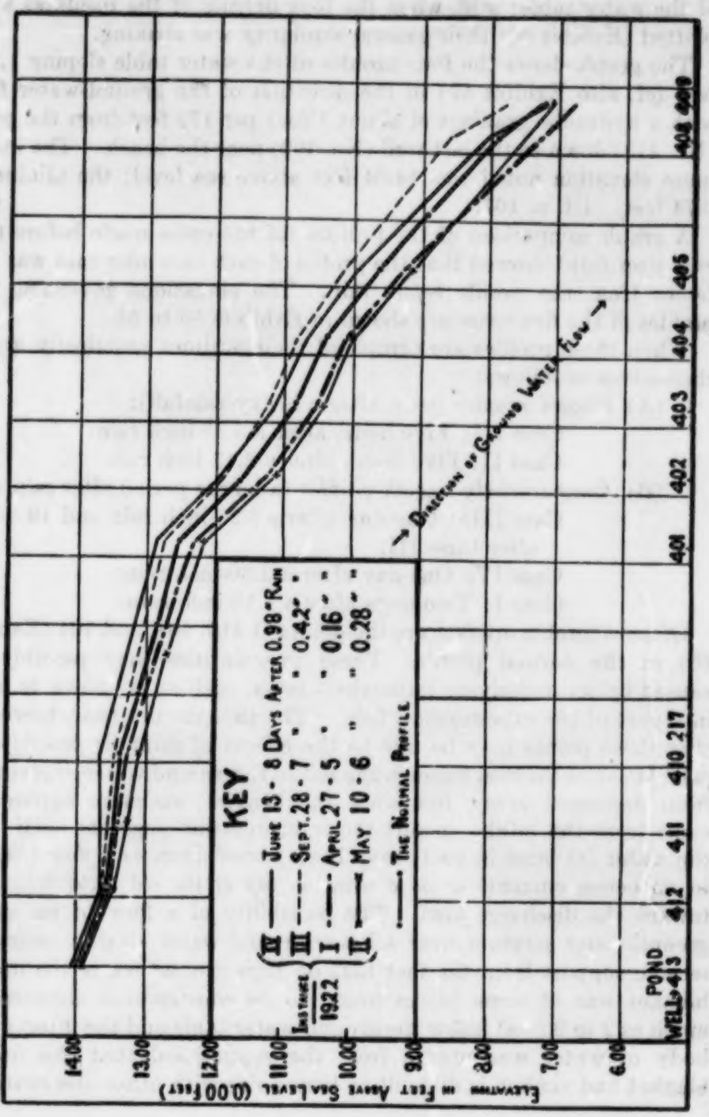


EXHIBIT 60.—*Profiles of the ground-water table, instances I to IV, and the normal profile*

The time intervals between the *instances* are not constants; they represent 153, 140, 106, 46, 33, and 12 days, respectively. Rains which occurred during these intervals naturally affected the profiles of the water table; still, when the four profiles of the *instances* were plotted (Exhibit 60) their general similarity was striking.

The graph shows the four profiles of the water table sloping 1,275 feet (cf. also Exhibit 57) in the direction of the ground-water flow with a hydraulic gradient of about 1 foot per 175 feet from the pond (No. 413) down to the last well (No. 409) near the beach. The maximum elevation noted was 14.04 feet above sea level; the minimum 6.74 feet. Cf. p. 167.

A graph comparison of the profiles (of the cases made before rain and after rain) showed that the profile of each case *after* rain was different from the profile *before* rain. The elevations governing the profiles of the five cases are shown in Exhibits 50 to 54.

When these profiles are compared their outlines practically group themselves as follows:

(A) *Rugged profiles* (soon after a heavy rainfall):
  Case III: Five hours after a 3.25-inch rain.
  Case II: Five hours after a 2.12-inch rain.

(B) *Comparatively smooth profiles* (a longer period after rainfall):
  Case IIIa: One day after a 3.25-inch rain and 19 hours after Case III.
  Case IV: One day after a 3.80-inch rain.
  Case I: Two days after a 1.12-inch rain.

Of considerable interest are the points at 410, 401, and 404 (Exhibit 60) in the normal profile. These irregularities may possibly be caused by an underlying impervious layer, such as is known to exist in a part of the experimental field. The thought lies near, however, that these points may be due to the effects of rainfall; possibly by percolation of the rain through the soil to the ground water or recharge from depressed areas, but since the heaviest recharge apparently came from the intake (pond) the interpretation suggests itself that the water (at least in part) may have *passed down as a flow* (similar to an ocean current) *or as a wave on top of the old water-table* and toward the discharge area. The possibility of a flow of an upper ground-water stratum over a lower ground-water stratum seems to receive support from the fact that on high ground water the uranin blanket was at some places found to be considerable distance (as much as 2 to 9 feet) below the ground-water table and the intervening body of water was uranin free; the supposition that the uranin blanket had sunken is difficult to harmonize with other observations.

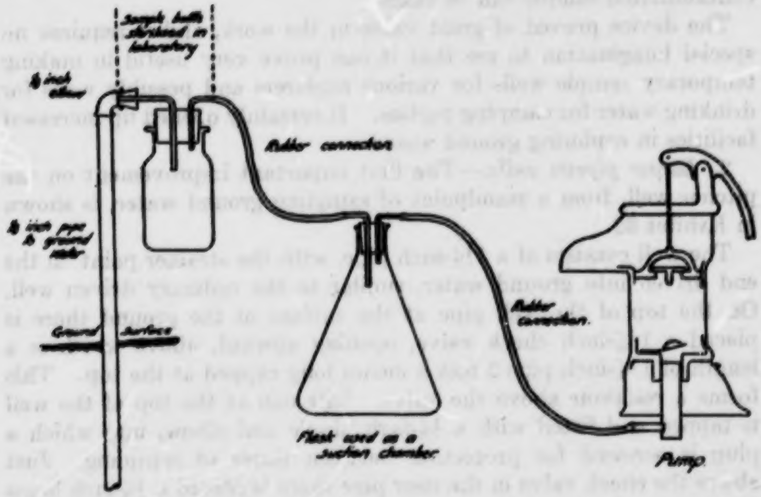
9. TYPES OF EXPERIMENTAL WELLS DEVISED FOR THE FORT CASWELL GROUND-WATER EXPERIMENTS

By H. R. Crohurst

The problem of obtaining underground water samples by a surgically aseptic technique and at not too great expense has at times presented difficulties, especially in view of the great number of tests that were necessary. Two types of wells were devised.

1. *Smaller pipette wells.*—One of these types is so simple in its installation that on one occasion, under very favorable circumstances two men installed 21 of them in about one hour. The time necessary for installation varies, of course, with the nature of the soil and the depth of ground water.

Exhibit 61.—*Smaller pipette well, with adapted pump, vacuum bottle, and connections*


Sample bottle sterilized in laboratory
⅛ inch elbow
Rubber connection
⅛ inch pipe to ground water
Ground surface
Rubber connection.
Flask used as a suction chamber
Pump

The well itself (Exhibit 61) consists simply of a ⅛-inch pipe of the desired length, with a copper screen at the lower end and an elbow with screw plug at the upper end. The hole in the ground is made by sinking a plunger. For this purpose either a ⅛-inch pipe threaded at one end on which a point is screwed was used, or, if the

resistance of the ground was greater, a solid iron bar was used. This plunger is forced to a desired depth, then cautiously withdrawn, and the well pipe is inserted. The well pipe can be flame-sterilized in the field by use of a plumber's torch; thus the well can be sunken bacteriologically sterile from air contamination. If by chance the screen becomes plugged, an automobile tire pump is attached at the upper end of the pipe and the screen is soon freed of obstruction.

To draw the samples, an ordinary pitcher pump has been adapted in the manner shown in the diagram (Exhibit 61). It will be noticed that the pump is screwed on to a short blind pipe which serves to hold the priming water. This pipe is tapped by a ⅛-inch short lateral pipe, connected by a rubber hose with one of the two glass rods extending through the rubber stopper of a retort. The second glass tube of the retort is connected by a rubber hose to one of the two glass tubes perforating the rubber stopper of a sample bottle, and the second glass tube of this bottle carries at its end a small perforated rubber stopper. The latter is then fitted into the elbow of the pipette well, after the screw plug has been removed. It is obvious that with proper precautions as to sterilization an absolutely noncontaminated sample can be taken.

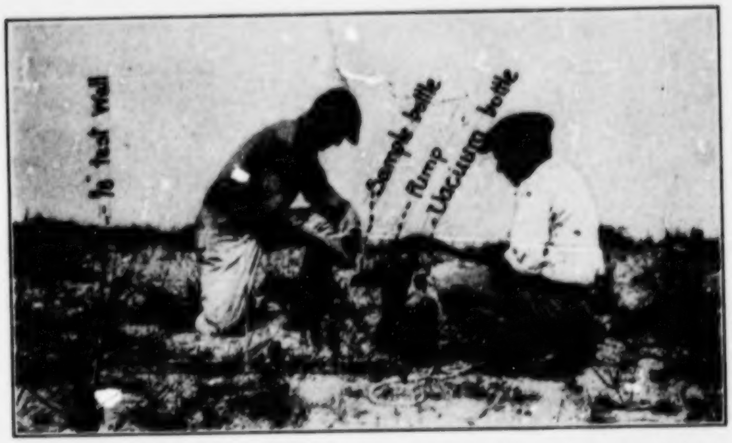
The device proved of great value in the work, and it requires no special imagination to see that it can prove very useful in making temporary sample wells for various explorers and possibly wells for drinking water for camping parties. It certainly opened up increased facilities in exploring ground water.

2. *Larger pipette wells.*—The first important improvement on the pitcher well, from a standpoint of sampling ground water, is shown in Exhibit 62.

The well consists of a 1¼-inch pipe, with the strainer point on the end driven into ground water, similar to the ordinary driven well. On the top of the well pipe at the surface of the ground there is placed a 1¼-inch check valve, opening upward, above which is a length of 1¼-inch pipe 2 feet 8 inches long capped at the top. This forms a reservoir above the valve. The cap at the top of the well is tapped and fitted with a ⅛-inch nipple and elbow, into which a plug is screwed for protection between times of sampling. Just above the check valve in the riser pipe there is placed a ⅛-inch brass stopcock, through which samples are drawn. Below the valve there is a ⅛-inch nipple, elbow, and short straight length of pipe, the end of which is fitted with a valve to permit the water to fall back into the well to the water table after the sample has been taken. In the straight length of pipe absorbent cotton is placed, through which the air passes that enters the well.

120a

Exhibit 63.—Photograph of Group 600 showing numerous wells



16' test well
Sample bottle
Pump
Vacuum bottle

Exhibit 64.—Photograph of part of method of taking water samples, with well pressed down

120 b

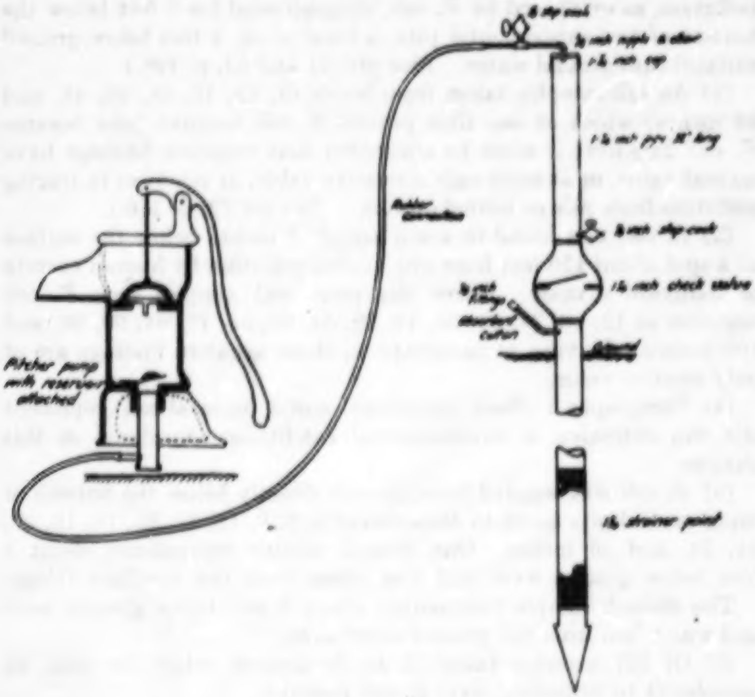
Sample bottle

Exhibit 65.—Photograph of part of method of taking water samples, with well lifted up

Exhibit 69.—Tree stump and peaty stratum exposed at low tide on beach. First line of dunes in background

In operation, the plug in the ¼-inch elbow at the top of the pipe is placed in the coupling in the ¼-inch fitting below the valve. The suction of the pump shown in Exhibit 62 is screwed into the fitting at the top and the pump operated in the usual manner; this raises the ground water into the reservoir above the valve. The weight of the water above the valve closes the valve and holds the water in the reservoir. The sample is taken from the ¼-inch brass stopcock. After the sample is taken the plug is removed from the fitting below the valve, and this allows the water in the casing to fall back to the water table; the plug is then placed in the fitting at the top of the pipe, after which the well is entirely closed until the next time for sampling.

EXHIBIT 62.—*Larger pipette well, with adapted pump and connections*



Rubber connection
¼-inch stop cock
1½-inch check valve
Pitcher pump with reservoir attached
1½ strainer point

10. EXPERIMENTAL DISTRIBUTION OF BACILLUS COLI IN THE SOIL UNDER AND NEAR PITS[1]

By C. W. Stiles and C. L. Pfau

Summary.—(1) Storm and flood conditions washed down fecal pollution, as evidenced by *B. coli*, through sand for 5 feet below the bottom of two experimental pits (a total of *ca.* 8 feet below ground surface) into ground water. (See pits 51 and 52, p. 126.)

(2) As soil samples taken from levels (6, 12, 18, 24, 36, 48, and 60 inches) which at one time proved *B. coli* positive later became *B. coli* negative, it must be concluded that negative findings have no real value, or at most only a relative value, as premises in tracing pollution from pits or buried excreta. (See pit 52, p. 126.)

(3) *B. coli* was found in a soil sample 6 inches below the surface at a spot about 150 feet from any known pollution by human excreta or barnyard manure. Below this point soil samples were *B. coli* negative at 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, 72, 84, 90, 96, and 102 inches. In view of paragraph 2, these negative findings are of only relative value.

(4) Paragraphs 1 (flood conditions) and 3 (natural soil) represent the two extremes of environmental conditions considered in this chapter.

(5) *B. coli* was isolated from the soil directly below the bottom of experimental pits down to distances of 4, 6, 8, 11, 12, 15, 16, 18, 20, 24, 28, and 36 inches. One 28-inch sample represented about 5 feet below ground level and was taken from the capillary fringe.

The 36-inch sample represented about 6 feet below ground level and was taken from the ground-water sand.

(6) Of 127 samples taken (3 to 36 inches) below the pits, 35 samples (4 to 36 inches) were *B. coli* positive.

(7) In view of the liquification and drying of excreta in a pit, fluid is released which may either (*a*) evaporate or (*b*) pass into the soil on four sides (capillary attraction) and at the bottom (gravity and capillary attraction) of the pit. On basis of paragraph 1, the assumption is made here that this gravity action would carry *B. coli* downward, and the thought lies near that capillarity would tend to carry *B. coli* both laterally and downward. This assumption is supported by the discoloration and odor of some of the soil samples radiating from the pits.

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[1] The samples were collected by Crohurst and Pfau; the bacteriological identifications were made and the notes were kept by Pfau prior to his resignation; the manuscript has been written by Stiles on basis of his familiarity with the experiments and from Pfau's notes; for the deductions Stiles alone is responsible.

(8) Combining paragraphs 1, 3, 4, and 7, the conclusion lies near that the *B. coli* in the 35 samples of paragraph 6 probably came from the overlying excreta. A theoretically conceivable alternative is that at least some of these *B. coli* were carried under the pit by the flowing ground water; this can not, however, invalidate paragraph 1.

(9) Combining paragraphs 2 and 8, the absence of *B. coli* in 92 of the 127 samples of paragraph 6 receives a potential explanation, namely, these portions of soil may have received and lost *B. coli* contamination.

(10) Of a total of 58 soil samples taken laterally from 10 pits, 5 samples (12 to 60 inches laterally) were positive for *B. coli*. At least 3 of these samples (including that from 60 inches away from the pit) appear to owe their infection to ground-water movement, so far as the evidence goes; and ground water may also account for a fourth positive sample. The fifth sample has not been brought into relation with the ground water; whether it was due to insect carriage is not clear from the evidence.

(11) Combining paragraphs 5 and 10, it seems clear that the experimental pits infected the ground water, and it seems practically clear that the infection was carried at least 6 feet laterally. (Other experiments (see p. 65) will show infection carried by ground water up to at least 232 feet.) The conditions of depth of pit and of ground-water elevation correspond to those in a considerable portion of the present pit privy area and this gives added emphasis to the importance of proper location of the privy.

(12) The general conclusion that material from these experimental pits gained access to the ground water and then was carried laterally is supported by well No. 1 of pit 1. Uranin placed in the pit in October, 1919, appeared in well No. 1 on August 2, 1920.

(13) The question as to factors influencing the distance to which *B. coli* can be carried by the ground water will be discussed elsewhere (p. 26, 88), but the point is emphasized here that the ground-water condition at the United States Marine Hospital Reservation, Wilmington, N. C., is a fair average of ground-water conditions over a very extensive Gulf-Atlantic coastal area where pit privies are more or less common.

Prior to the Fort Caswell studies (p. 14) on the movement of *Bacillus coli* in the ground water certain studies were conducted on experimental pits at the United States Marine Hospital Reservation, Wilmington, N. C.

A number of experimental pits, simulating pit privies, were dug at various points in the reservation. In some instances these were sheathed, crate fashion, to prevent the caving in of the sand; in some instances the sheathing was omitted. The excreta used were the regular night-soil collections of the city scavenger and consisted of a mixture of material from open-back and from box-and-can privies; accordingly, the excreta averaged a thicker consistency than can-privy material and a thinner consistency than open-back surface privy night soil.

The only difference as to dosage between these experimental pits and a regular pit privy was that in the former all the dosing occurred during one to several days, each time in large quantity (about one scavenger's wagon load, namely one-half to three-quarters cubic yard), while in the latter the dosing occurs in small quantities (urine plus feces) daily over a considerable period (months to years) of time.

In order to carry out the pit-privy conditions as respects rain water, many of the pits were protected by a wooden roof which shed the rain from the pit itself. The rain water ran down into the sand at the sides of the pit, as occurs in case of a pit privy, with the constant possibility (also as in the case of pit privies) that occasionally some water might seep into the pit; our general experience is, however, to the effect that water tends to seep perpendicularly both through sand and sawdust rather than diagonally, although there is a slight lateral seepage by capillarity or by flow, according to the quantity of the water.

Some of the soil samples were obtained by first excavating perpendicularly a pit parallel to and at the side of the experimental pit and then making horizontal borings under the latter. This method was later changed as follows: The excreta were taken out of the experimental pit down to the sand bottom; then perpendicular borings were made.

It is needless to state that the soil borer was thoroughly sterilized (by flaming with a plumber's torch) before each sample taking, in order not to carry the bacteria of a higher level to the sample of a lower level. The technique followed was academically extreme, and the technique of taking the soil samples is considered to be beyond criticism.

The only pronounced difference in technique between the experiments of this series and those of the ground-water studies at Fort Caswell is that uranin was used in the latter but, with one exception (pit 1), not in the former. Thus in the Fort Caswell experiments the presence of green was proof that green uranin had actually come from the pits; in the Wilmington observations this absolute proof is lacking except for pit 1, but deductions can be based in some instances upon the discoloration or the odor of the sand.

The soil borings which come into present consideration can be divided into five groups: A, B, C, D, and E. Of these, Groups A and E represent the environmental extremes.

Group A.—Natural soil at a high point considerably removed (about 150 feet) laterally from any known point of pollution of the soil with either human excreta or barnyard manure.

Group B.—At points 3 to 78 inches laterally from known pollution of the sand (namely, pits containing human excreta).

Group C.—At points and levels directly under covered pits containing human excreta at the time of taking the samples or from which the excreta had recently been removed.

Group D.—Directly beneath an uncovered area in which human excreta had been experimentally buried superficially.

Group E.—Pits from which human excreta had recently been removed and into which, prior to said removal, water had been run to simulate storm and flood conditions.

As the two environmental extremes are represented by A and E, these may be expected to show extreme differences in distribution of *B. coli* if any differences exist. Accordingly, it is well to consider A and E first.

GROUP A: NORMAL SOIL.—In April, 1920, soil borings were made and samples of sand taken from depths varying from 6 inches to 8 feet 6 inches below the surface on the reservation at a high point quite removed from any spot which had been experimentally polluted with human excreta or which was known to have been fertilized with manure. Bacteria were found in all samples.

B. coli was found at 6 inches but not at 12 inches or below.

Gas-producing bacteria (not confirmed as *B. coli*) were found at 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, 72, 84, 90, and 96 inches.

Samples at 78 and at 102 inches were negative both for *B. coli* and for gas.

In general, the bacterial count decreased in the samples taken at depths of from 6 inches to 90 inches, but it increased again as the capillary fringe and the ground water (96 inches, 102 inches) were reached. In detail the general bacteria-per-gram counts were:

6 inches	280,000	60 inches	700
12 inches	19,000	66 inches	800
18 inches	31,000	72 inches	700
24 inches	26,000	78 inches	1,200
30 inches	29,000	84 inches	400
36 inches	12,000	90 inches	100
42 inches	16,000	96 inches (capillary fringe)	3,300
48 inches	13,000	102 inches (ground-water table)	1,200
54 inches	8,000		

An interesting—possibly significant—point is that in the capillary fringe (96 inches) the bacterial count rose to 3,300 as compared with 100 at 90 inches.

It will be noted that while *B. coli* was found in the single sample taken at 6 inches it was not found in the 16 samples taken at deeper points (12 to 102 inches). This point will be strengthened by certain borings in Group B, but in Group E the proof will be given that the absence of *B. coli* from a given stratum on a given date is not proof as respects the condition at the same point on other dates.

GROUP E: STORM AND FLOOD CONDITIONS.—Three pits (Nos. 50, 51, and 52) were dug, 3 by 3 by 3 feet. Excreta collected from can privies were screened through ordinary wire fly screening.

Pit 50.—April 30, 1920, dosed with the very fluid excreta. Soil samples taken September 20; *B. coli* found only at 12 inches. (Compare Group A.)

Pit 51.—April 30, 1920: Residual excreta, about 13 gallons (screened from the excreta used in pit 50) were placed in pit 51 (3 by 3 by 3 feet); a fairly good stream of water from a garden hose was run into the pit for about 15 hours; extreme storm and flood conditions were thus simulated. The object of the experiment was to determine whether pollution would be washed down (Exhibit 66) through the sand to ground water.

May 3 (3 days later): *B. coli* was found at 6, 12, 18, 24, 36, 48 (capillary fringe), and 60 inches (ground-water table), below the bottom of the pit (the latter 3 feet below surface of ground).

Thus, in contradistinction to Group A (with natural conditions of soil moisture), under these flood conditions *B. coli* was found consistently down to 5 feet below the bottom of the pit (=8 feet below surface of the ground).

On May 11 (11 days after original pollution) and June 2 (33 days after original pollution), July 5 (66 days), and July 26 (87 days), *B. coli* was recovered at the same seven levels (6, 12, 18, 24, 36, 48, and 60 inches) below the bottom of the pit. By June 2 the ground water had fallen so that the soil samples taken on the last three dates at 60 inches were not very moist.

It will be noticed that pollution persisted 87 days (practically three months) at all seven depths. Samples were not taken after July 26.

The natural inference is that the pollution came from the pit.

Pit 52.—May 4: Excreta from can privies were screened; the fluid portion was placed in pit 50 (see above); the solid residuum (about 10 gallons) was placed in pit 52 (3 by 3 by 3 feet); water was run into pit 52 for a total of about eight hours (on May 6 and 10); pit was cleaned May 10.

May 10 (6 days after original pollution; 4 days after first artificial flood): *B. coli* found (Exhibit 66) at 6, 12, 18, 24, 36, 48, and 60 inches (3 inches above ground-water table) below bottom of pit (the latter 3 feet below surface of ground).

July 6 (33 days after original pollution, 31 days after first flood): *B. coli* as on May 10.

July 27 (54 and 52 days): Ditto.

September 10 (98 and 96 days): *B. coli* recovered at 12 inches, but not at 6, 18, 24, 36 (capillary fringe), and 48 inches (ground-water table); 60 inches was in ground water and no satisfactory sand sample could be held in the soil borer.

October 28 (177 and 175 days=nearly 6 months): *B. coli* not found at 6, 12, 18, 24, 30, 36, 42, 48, 54, and 60 inches. The original infection appears to have died out in about 5 ½ months, including the hot summer season.

Thus the results of experiment in pit 51 were fully confirmed as to penetration by the pollution under flood conditions; in addition, it will be noticed that only one soil sample (at 12 inches) out of six was positive for *B. coli* 96 days after the first flood, and that 175 days after the first flood 10 soil samples, 6 to 60 inches, respectively, were *B. coli* negative.

Holding in mind the two points that—

(1) In the natural soil *B. coli* was found at 6 inches, but not deeper; and

(2) Under flood conditions (movement of water) *B. coli* was washed down 5 feet below the bottom of 2 pits (i. e., a total of 8 feet below surface of ground) to ground water—

it seems possible to interpret the data reported for Groups B, C, and D.

EXHIBIT 66.—*Table of soil examinations, pits 51 and 52*

[Key: c=*B. coli* positive; g=gas positive, *B. coli* negative]

Depth (inches)	Pit 51					Pit 52				
	May 3	May 11	June 2	July 5	July 26	May 10	July 6	July 27	Sept. 10	Oct. 28
6	c	c	c	c	c	c	c	c	g	g
12	c	c	c	c	c	c	c	c	c	g
18	c	c	c	c	c	c	c	c	g	g
24	c	c	c	c	c	c	c	c	g	g
30										g
36	c	c	c	c	c	c	c	c	g	g
42										g
48	c	c	c	c	c	c	c	c	g	g
54										g
60	c	c	c	c	c	c	c	c		g

GROUP B.—*B. coli* CONDITIONS LATERALLY FROM EXPERIMENTAL PITS.—A total of 69 soil samples was taken from various depths, 6 to 78 inches laterally from 10 experimental pits, and *B. coli* was recovered five times, as follows:

12 inches out, 18 inches above bottom of pit	1 time.
12 inches out, 12 inches below bottom of pit	2 times.
36 inches out, 6 inches below bottom of pit	1 time.
60 inches out, 3 inches below bottom of pit	1 time.

EXHIBIT 67.—*Composite table of soil examinations from above and below bottom of pits and laterally from pits*

[Key: c=one sample *B. coli* positive; n=one sample *B. coli* negative]

Inches above or below bottom of pits	Laterally from pits												
	6 inches	12 inches	18 inches	24 inches	30 inches	36 inches	42 inches	48 inches	54 inches	60 inches	66 inches	78 inches	Total
18 above		c											c
10 above		n											n
1 above						n				n			2n
3 below										c			c
6 below	n	n	n	n	2n	c	2n	n	2n	2n	n	n	c 15n
9 below	2n	2n	2n	2n	2n	2n	2n	2n	2n	2n			20n
12 below		2c 3n											2c 3n
21 below	2n	2n	2n	2n	2n	2n	2n	2n	2n	2n			20n
36 below										n			n
42 below										n			n
54 below										n			n
Total	5n	3c 9n	5n	5n	6n	c 5n	6n	5n	6n	c 10n	n	n	5c 64n

Making a composite pit (Exhibit 67) of 10 pits available for Group B, we obtain the following data:

Analyzed, the 5 cases of *B. coli* positives are as follows:

Pit 5.—November 17–18, 1919: Pit about 3 by 3 by 3 *feet*; side sheathed. Dosed with fairly thick can-privy excreta.

March 20, 1920: *B. coli* positive directly under the pit at 4, 6, and 12 inches. Dark brown to black sand, fecal to ammoniacal odor.

B. coli positive 12 inches laterally at point 12 inches below bottom of pit; black sand, musty odor. This represents about 4 feet below surface of ground. The color and odor of the sand suggest that the infection came from the pit.

Pit 6.—November 19–25, 1919: Pit about 3 by 3 by 3 *feet*; sides sheathed. Dosed with fairly thick can-privy excreta.

March 20, 1920: *B. coli* positive directly under the pit at 6, 12, and 18 inches. Sand reddish, brown, to black.

B. coli positive 12 inches laterally at point 12 inches below bottom of pit; sand brownish black, very moist. This point represents about 4 feet below surface of ground and is in the capillary fringe. The color of the sand combined with the presence of *B. coli* under the pit at the same depth suggests that this infection came from the pit and that it was carried laterally by the flow of ground water.

Pit 7.—November 26–30, 1919: Pit about 3 by 3 by 3 *feet*; sides sheathed. Dosed with fairly thick excreta.

March 25, 1920: Samples taken laterally to the east; exact direction of groundwater flow at this particular point was not tested, but in general the flow tends somewhere between west to east or southwest to northeast. Bottom of pit 6 inches in ground water.

B. coli positive as follows (in reference to bottom and east side of pit):

12 inches east, 18 inches above (corresponding to layer of excreta).

5 feet east, 3 inches below; thus this sample came from a point between high and low ground water.

Pit 13.—December 21–26, 1919: Pit 3 by 3 by 6 *feet*; sides sheathed solidly with boards, but naturally subject to leakage.

October 1, 1920: Pit emptied. Bottom of pit is 8 inches in ground water.

October 9, 1920: Ground water has dropped considerably. *B. coli* positive 36 inches laterally, 6 inches below; thus this sample came from a point between high and low ground water.

From the foregoing it is clear that of the 5 *B. coli* positive samples, that from—

Pit 5, 12 inches out, shows evidence (color, odor) that the pollution came from the pit.

Pit 6, 12 inches out, is in the capillary fringe, which during high ground water would become ground (phreatic) water layer.

Pit 7, 12 inches out, shows evidence that it might once have been in either capillary fringe or possibly in ground water, but the evidence is not positive; 5 feet out, evidence is clear that this has at one time been in ground (phreatic) water.

Pit 13, 3 feet out, 6 inches below; evidence is clear that this was once in ground (phreatic) water.

Thus of the 5 *B. coli* positive specimens, 3 show that the spots from which they were taken were clearly affected by and were once in ground (phreatic) water; and this point is suggestive also in a fourth sample; the fifth sample is unexplained.

As theoretically possible alternatives, in explaining the cases of lateral extension of pollution, it is necessary always to consider the insect larvæ in the night soil. We have repeatedly found these larvæ wandering out laterally 6 to 36 inches and under favorable conditions *B. coli* infection might be carried by them.

The 63 negative specimens might be accounted for theoretically in either of two ways—(*a*) the soil had never become infected at these points, or (*b*), though the soil was once infected, *B. coli* could have died out. (See p. 126, Group E, pit 52.)

In this general connection reference should be made to pit No. 1. Although all soil samples below 6 inches were *B. coli* negative on October 11–25, 1920, well No. 1 (6 feet away) showed uranin on August 2 to 17, 1920, and *B. coli* on April 23, May 22 and 24, June 1, 7. 9, 10, 11, 12, 14, 16, 18, 19, and 21, July 7, 8, 9, 12, 14, 15, 16, 19 and 21, and August 4. As the uranin was used only in pit 1, the uranin pollution must have come from this pit; accordingly, material from the pit had reached ground water and had flowed to the well. This case, taken in conjunction with the pits of Group B and with the *B. coli* infection of well 1, justifies the conclusion that all the necessary links in an experimental demonstration have been presented to prove that pollution in a pit can travel down at least 3 feet to ground water, then flow laterally to at least 6 feet (for greater distances, see p. 65), and thus infect a well.

The practical question remains to be answered as to how far the infection can flow laterally. This point is discussed in another part of this report. (See p. 65.)

GROUP C: B. COLI CONDITIONS DIRECTLY UNDER A PIT PRIVY.—Ordinary pits were dug in sand, usually sheathed to prevent caving, and covered to prevent direct ingress of rain water. Excreta were dumped into these pits by the city night-soil scavenger; some loads of excreta were fairly solid; some were less solid. Later, soil samples were taken, either by boring under the pit from the side or the excreta were removed and the boring was perpendicular. Seventeen pits in this group furnished 127 soil samples taken *under* (not laterally from) the bottom of the pits. Tabulating these 127 samples into a composite pit (Exhibit 68), the results obtained are as follows:

EXHIBIT 68.—*Composite of 17 pits; status of* B. coli *at different depths under pit floor*

Inches below bottom of pit	Total number of samples	B. coli positive	B. coli negative; gas positive	B. coli and gas negative	Inches below bottom of pit	Total number of samples	B. coli positive	B. coli negative; gas positive	B. coli and gas negative
3	1		1		27	1		1	
4	2	2			28	1	1		
5	1		1		30	5		2	3
6	19	11	8		33	2		1	1
8	5	2	3		36	7	1	4	2
11	1	1			37	1		1	
12	19	6	11	2	38	1			1
13	1		1		42	3		3	
14	1		1		43	1		1	
15	3	3			48	6		4	2
16	1	1			54	4		3	1
18	20	5	12	3	60	4		2	2
20	1	1			66	2		2	
23	1		1						
24	13	1	8	4	Total	127	35	71	21

It will be noticed that *B. coli* was found down to 36 inches below the bottom of the composite pit. As *B. coli* was found at 6 inches in the normal sand of Group A, there is nothing startling in the fact that it was found in 13 samples at 4 inches (2 samples) and 6 inches (11 samples) under the excreta, so that these 13 samples might be ignored; however, this is not to be taken as a claim that the pollution at 4 and at 12 inches did not come from the pit, but only that it is the deeper samples which present greater interest.

Analyzing the deeper *B. coli*, especially those from 24 to 36 inches the following data are obtained:

At 28 inches.—Pit 5: Bottom of pit about 3 feet below ground level, so that this sample was in reality 6 feet (72 inches) below ground level.

November 17–18, 1919: Pit dosed with fairly thick night soil.

March 20, 1920: Excreta in pit had become more liquid, volume had shrunken very much, so that the top level of the excreta was 2½ feet lower than on November 18, 1919. *B. coli* at 4 inches, 6 inches, and 12 inches. Dark brown to black sand; fecal to ammoniacal odor.

March 31, 1920: Pit emptied. *B. coli* negative at 3, 8, 13, 18, 23, 33, 38, and 43 (soil very wet) inches; *B. coli* positive at 28 inches (soil moist=capillary fringe). Bacterial counts (per gram) were:

3 inches	1, 610, 000	28 inches	930, 000
8 inches	891, 000	33 inches	383, 000
13 inches	600	38 inches	31, 000
18 inches	400	43 inches	150, 000
23 inches	1, 520, 000		

April 2, 1920: *B. coli* positive (and general bacterial counts per gram) at 6 inches (and no count), 11 inches (and 2,500,000), 16 inches (and 1,250,000), 20 inches (and 120,000).

B. coli negative (and general bacterial count) at 24 inches (and 110,000), 27 inches (and 50,000), 30 inches (and 40,000), 33 inches (and 40,000), 37 inches (and 130,000).

The important points to be noticed are:

(*a*) That *B. coli* was found March 31 at 28 inches below the bottom of the pit (about 5 feet below surface of ground);

(*b*) At this time this point was in the capillary fringe;

(*c*) The bacterial count was 930,000; and

(*d*) There had been extensive liquefaction and drying of the excreta.

At 36 inches.—Pit 6: Bottom of pit was about 3 feet below surface of ground, so that this sample was in reality about 6 feet below ground level.

November 19 to 25, 1919: Pit dosed with fairly thick excreta.

March 20, 1920: *B. coli* positive (and general bacterial count per gram) at 6 inches (and 5,000) 15 inches (and 1,200,000, sand moist), 18 inches (and 210,000, soft dark sand).

April 27, 1920: Pit emptied.

April 28, 1920: *B. coli* positive (general count omitted) at 6, 12, 18, 24, and 36 (ground water) inches.

The important points to notice are:

(*a*) *B. coli* was found down to 36 inches below the bottom of the pit (about 6 feet below ground level); and

(*b*) This point was in ground water.

Samples from beneath the following pits were entirely negative for *B. coli* as follows:—

Pit 2.—November 14, 1919: Pit dosed with fairly thick excreta.

March 19, 1920: *B. coli* negative at 5, 8, and 12 inches.

April 23, 1920: *B. coli* negative at 6, 12, 18, 30, 42, 54, and 66 inches.

All samples were above capillary fringe.

Pit 3.—November 15, 1919: Pit dosed with fairly thick excreta.

March 16, 1920: *B. coli* negative at 8, 14, and 18 inches.

April 27, 1920: *B. coli* negative at 6, 12, 18, 24, 36, 48, and 60 inches.

All samples were above capillary fringe.

Pit 12.—December 19–20, 1919: Pit 4 by 4 by 5½ feet deep. Dosed with fairly thick can-privy excreta.

October 3: *B. coli* negative at 6, 12, 18, and 24 inches.

Pit 13.—December 21–26, 1919: Pit 4 by 4 by 6 feet deep. Dosed with fairly thick can-privy excreta.

October 1, 1920: Pit emptied; bottom of pit 8 inches in ground water.

October 9, 1920: Ground water had dropped considerably. *B. coli* negative at 6, 12, 18, and 24 inches.

Pit 18.—January 13–16, 1919: Pit 3 by 4 by 4 feet deep. Dosed with fairly thick can-privy excreta.

October 26: *B. coli* negative at 6 (wet soil), 12 (wet soil), and 18 (ground water) inches.

Samples from beneath the following pits were *B. coli* positive in upper layers of sand, as follows—

Pit 1.—This is the only pit in which uranin was used.

February, 1920: Pit enlarged to 3 by 3 by 3 feet. Sides sheathed.

February 2.—April 23, 1920: Dosed daily for 81 days with can-privy excreta equal to the accumulation of 17 persons; total amount, 175.6 gallons. These privies were under the supervision of and were scavenged by our own force.

October, 1919: Uranin placed in pit.

May 24, 1920: *B. coli* recovered from well No. 1, 6 feet distant from pit on 24 days, April 23 to August 4.

August 1, 1920: Pit emptied. Excreta had decreased from 175.6 gallons down to 33 gallons; accordingly, there had been considerable liquefaction and evaporation.

August 2, 1920: Uranin recovered from well No. 1, 6 feet distant from pit, on August 2 (first appearance), 3, 4, 5, 6, 9, 10, 11, 12, 13, 16, 17, and 19. Uranin also appeared in well No. 8.

October 11: *B. coli* positive at 6 inches; negative at 12, 18, 24, 30, 36, 42, 48 (wet), 54, 60, and 66 inches. All samples showed some moisture.

October 25: *B. coli* negative at 6, 12, 18, 24, 30, 36, 42, 48, and 54 (ground water) inches.

Since pit No. 1 is the only pit on the entire reservation in which uranin was used, the conclusion can not be escaped that material (uranin) placed in this pit traveled from the pit to two wells (Nos. 1 and 8), and the conclusion lies near that the *B. coli* in the well No. 1

recovered, on 24 days, April 23 to August 4, came from the same source. But it is to be noticed that later (October) *B. coli* infection directly under the pit was not found—obviously it had died.

Pit 4.—November 16, 1919: Pit dosed with fairly thick can-privy excreta.

March 9, 1920: *B. coli* positive at 4, 8, and 15 inches.

April 28, 1920: *B. coli* positive at 6 inches, negative at 12, 18, 24, 36, 48, and 60 inches.

Pit 11.—December 14–18, 1919: Pit 3 by 3 by 5 feet deep. Dosed with fairly thick can-privy excreta.

October 9, 1920: *B. coli* positive at 12 inches; negative at 6 and 18 inches.

Pit 14.—December 30–31, 1919: Pit 3 by 3 by 3 feet. Dosed with fairly thick can-privy excreta.

October 26, 1920: *B. coli* positive at 6 and 18 inches; negative at 12 and 24 inches.

Pit 15.—January 3, 1920: Pit 3 by 3 by 3½ feet. Dosed with fairly thick can-privy excreta.

October 2, 1920: Pit emptied.

October 26, 1920: *B. coli* positive at 18 inches; negative at 6, 12, and 24 (ground water) inches.

Pit 16.—January 3–4, 1920: Pit 3 by 3 by 3 feet. Dosed with fairly thick can-privy excreta.

October 2, 1920: Pit emptied. *B. coli* in excreta.

October 26, 1920: *B. coli* positive at 6 (moist soil), 12 (moist), and 18 (ground water) inches.

Pit 17.—January 8–11, 1920: Pit 3 by 3 by 3 feet. Dosed with fairly thick can-privy excreta.

October 2, 1920: Pit emptied. *B. coli* in excreta.

October 26, 1920: *B. coli* positive at 6 inches; negative at 12, 18, and 24 inches.

Pit 19.—January 18–22, 1920: Pit 3 by 3 by 3 feet deep. Dosed with fairly thick can-privy excreta.

October 4, 1920: Pit emptied. Bottom of pit 12 inches in ground water. Excreta *B. coli* positive.

October 26, 1920: *B. coli* positive at 6 (wet) and 12 inches (ground water).

Pit 20.—January 24–25, 1920: Pit 3 by 3 by 4 feet deep. Dosed with fairly thick can-privy excreta.

October 4, 1920: Pit emptied. Bottom of pit 6 inches in ground water.

October 26, 1920: *B. coli* positive at 6 and 12 inches; negative at 18 (ground water) inches.

GROUP D.—*Superficial burial of excreta:* In view of the common method of superficial burial of excreta, the question arises as to whether pollution sinks down into the ground, either by capillarity or by being washed down by gravity rain water.

Obviously, the same principles as to capillarity obtain in this case as in the case of feces in a pit privy, except that there is a capillarity upward as well as downward and laterally.

Obviously, also, the same general principles of gravity obtain here as in storm and flood conditions in a pit privy. (See p. 126.)

Three experiments were made with superficial burial as follows:

(1) During May, 1919, fairly thick feces from surface privies were buried in 9 parallel trenches, 20 feet long, 1 foot deep, by 1 foot

wide, with a distance of 18 inches between trenches. These trenches were dug in sandy soil and the excreta put into them to a depth of 6 inches and then covered with 6 inches of sandy soil.

In February, 1920, one of these trenches was opened for examination. A vertical section through the trench showed a layer-cake effect; on top was a layer of light-colored sand; then came a dark, almost black, layer of excreta, and below this another layer of light-colored sand which showed very little, if any, discoloration from the excreta that had been placed above it. The excreta layer, originally 6 inches deep, had contracted to a thickness of approximately 2 inches. Examination of this excreta layer showed it to be very dry and friable and without odor.

Samples of the excreta layer and of the sand layer below it were taken for bacteriological examination, with results as follows:

B. coli was positive in quantity samples of the excreta layer for grams 10, 1, 0.1, 0.01, 0.0001, and 0.00001. General bacterial count per gram, 1,760,000.

B. coli was positive in quantity samples of the sand 4 inches below the excreta layer for grams 10, 1, 0.1, 0.01, and 0.001, and negative for 0.0001 and 0.00001. General bacterial count, 380,000.

(2) During June, 1919, fairly thick surface excreta were buried in bulk in a hole 10 feet square by 1 foot deep, dug in sandy soil. The excreta were dumped into this hole to a depth of 6 inches and then covered with 6 inches of sand.

In February, 1920, this place was opened for examination. Vertical section showed the layer-cake effect also, but with this difference, that here the excreta layer was greenish rather than black and about the same consistency as stiff dough. There was also some odor present.

Samples of the excreta layer and of the sand layer below it were taken for bacteriological examination, with results as follows:

B. coli was positive in quantity samples of the excreta layer for grams 10, 1, 0.1, 0.01, and 0.001; negative for 0.0001 and 0.00001. General bacterial count per gram, 10,000,000.

B. coli was positive in quantity samples of sand 4 inches below the excreta layer for grams 10, 1, 0.1, 0.01; negative for 0.001, 0.0001, and 0.00001. General bacterial count, 350,000.

It is interesting to note from these two tables the comparatively low bacterial count obtained in the soil only 4 inches from and directly below the excreta.

(3) During July and August, 1919, fairly thick surface privy excreta were buried in the woods on the reservation. A hole was dug 15 feet square by 18 inches deep. Into this the excreta were dumped from time to time and lightly covered with a layer of rich wood

loam. When the hole was filled the mass of excreta was covered with about 6 inches of rich black wood loam.

When the buried excreta were examined in February, 1920, no pronounced evidence of putrefaction was found. The material still looked more or less like surface privy excreta, and it still possessed the typical odor of old excreta. The moisture content was apparently still very high. The location of this experiment was in the lowest part of the reservation where the ground water is fairly close to the surface of the ground. Furthermore, it was in a woods where the drying effect of sun and wind was much lower than in the other two experiments. Samples of the excreta were taken for bacteriological examination with results as follows:

B. coli was positive in quantity samples in grams 10, 1, 0.1, 0.01, 0.001, 0.0001, and 0.00001. General bacterial count per gram, 3,600,000.

11. BACTERIOLOGICAL TECHNIQUE USED AT FORT CASWELL

By G. E. Thomson

In its last analysis the bacteriological argument in this bulletin is based on two fundamental premises, namely,

a (*b*) Certain bacteria (interpreted as fecal *Bacillus coli seu Escherichia*) were isolated from trenches polluted with uranin and excreta and from wells and the soil on the downstream side (as respects ground-water flow) of said trenches in experimental plots which showed uranin pollution; and

b (*a*) These same bacteria were not recovered by the same bacteriological technique from water samples (from wells) and from soil samples taken outside of the uranin-polluted portions of the field.

On the basis of these fundamental premises, the question of whether the determination of these bacteria as *Bacillus coli* is in harmony with the determinations of *B. coli* s. l. or s. r. by various other authors as of the dates 1890, 1900, 1920, etc., is (from our viewpoint) purely an academic matter, however interesting this taxonomic point may or may not be considered. Notwithstanding this conception of the data, some readers may desire to know the general technique followed.

With the definite claim that the taxonomic point under consideration is inconsequential to our argument, the following details are given:

1. *Sterilization.*—Sterilization was carried out to an academic extreme. Not only was the usual laboratory sterilization of media, instruments, glassware, etc., practiced, but the pipette wells were sterilized before being driven and the aperture of each well was flamed with a plumber's torch (Exhibit 65) both before and after sample taking and closed by a plug during intervals between samples.

2. *Sample bottles.*—Two types of glass sample bottles were used.

a. A 4-ounce ground-glass stoppered bottle capped with metal foil; and

b. A 5-ounce glass bottle (see Exhibit 65), provided with rubber stopper through which were two glass tubes (one to connect with the well by means of a small rubber stopper; the other to connect by rubber tube with the vacuum bottle, the latter being connected by rubber tube with the pump). (See Exhibits 64 and 65.) These bottles were protected by sterilized cotton, which was protected by a tin cap (made from commercial tobacco cans). (See Exhibit 64.) Although the bottles, etc., were sterilized in the laboratory, the rubber stopper which connected with the well was flamed immediately before and after using (in sample taking).

The large number of negative controls A and B place the technique beyond criticism.

3. *Laboratory technique.*—Standard Methods of Water Analysis of the American Public Health Association (editions 1920-1925) were taken as basis (differentiation through inoculation to lactose broth, growth on Endo medium, reaction to Gram stain). During the first six months certain additional steps were used, but later discontinued as unnecessary; after this period the routine was reduced to Standard Methods, 1925, page 108, to which were added two steps, i. e., the methyl red and Voges-Proskauer tests (pp. 111 and 112) (with cultures held five days, as per Standard Methods, 1923, p. 107).

4. *Media.*—Liebig's meat extract was used; Digestive Ferments Co.'s peptone was used for general media; Witte's peptone was used for the methyl red and Voges-Proskauer test. Nutrient agar was made according to Standard Methods, 1925, except for the addition of 5 grams of sodium chloride per 1,000 cubic centimeters. The Endo medium was made with the addition of 5 grams of sodium chloride and adjusted to a pH of 7.6.

5. *Time of examination.*—Usually two to three hours elapsed from time of sample taking to beginning of laboratory study (at Fort Caswell), but this was extended to about 24 hours when samples were studied at Washington. (See p. 64.)

6. *Personal equation.*—As several persons were engaged in the bacteriological work, the personal equation was reduced to a minimum by close association in work until routine was established and in some cases by study of the same samples by two aides.

12. REPORT ON THE GEOLOGY AND GROUND-WATER HYDROLOGY OF THE EXPERIMENTAL AREA OF THE UNITED STATES PUBLIC HEALTH SERVICE AT FORT CASWELL, N. C.

By Norah Dowell Stearns, Ph. D., United States Geological Survey

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PHYSIOGRAPHY

The experimental area is situated on Oak Island, about 4 miles west of Fort Caswell, N. C. Oak Island is not really an island but comprises a strip of the mainland extending in an east-west direction and bounded by Elizabeth River on the north and by the Atlantic Ocean on the south. It varies in width from a few hundred feet to about a mile and a half. In recent geologic time the land has been successively elevated and depressed. The last event was depression and a consequent drowning of the river valleys. Oak Island is the remains of an old divide, now partially separated from the mainland by the drowned valley of Elizabeth River.

Proceeding inland from the ocean, at the experimental area, the following features are noted: (1) A strip of beach about 50 feet wide at high tide; (2) a belt of low dunes about 400 feet wide; (3) a terrace scarp and level of the red sand formation about 400 feet wide; (4) a short belt of high dunes on the red sand terrace about 200 feet wide; (5) the steep back slope of the dunes; (6) a terrace area of red sand covered with vegetation and containing depressions occupied by swamps and ponds; and (7) Elizabeth River Valley, comprising a bank, an area of reeds and rushes, a fringe of marsh grass, and the river itself.

There is practically no drainage. A few tiny brooks were seen after a rain draining from a swamp area to Elizabeth River. The Southport Road follows the high land and hence marks fairly closely the divide of any possible drainage. The surface sands are very porous and absorb nearly all the rain. In the depressions among the dunes and in the ponds and swamps of the terrace belt the rain is often held for a short time until it seeps into the ground.

Beaches.—At the high-tide line the beach slopes steeply seaward, but from the mean tide line to the low-tide line it slopes more gently. About at the mean tide line a layer of peat crops out, with tree stumps a few feet high standing erect (Exhibits 69–70). West of the experimental area this peat outcrop is lacking, but it extends toward the east for probably half a mile. The beach sand is fine and contains much comminuted shell.

Dunes.—About 50 to 100 feet from the high-tide line is a belt of sand dunes about 5 feet high. Back of these dunes are smaller dunes and level areas interspersed with depressions. In the depressions the water table is usually only a few feet below the surface. They have moist soil, contain considerable grass and other vegetation, and are evidently areas of evaporation.

On the terrace of red Pleistocene sand is a second belt of dunes (Exhibit 71–73) which is about 200 feet wide in the experimental area but which disappears east and west of this area. This dune belt comprises the highest land and has an altitude of about 30 feet above low tide. The dunes are about 10 feet above the terrace level. The back slope of the dune area is precipitous. The dune sand is chiefly whitish blown sand and lies upon the red sand of the terrace. It is constantly shifting. During the summer the prevailing winds are from the south or southwest and the sands encroach upon the scrub oaks to the north and northeast, but during the winter the strong winds blow from the north or northeast and some of the sand is blown back again. The dunes are bare for the most part, but in places have a very sparse vegetation, chiefly grass and sand weeds.

Pleistocene terrace.—About 400 feet inland from the high-tide line is the scarp of the terrace of red sand. This scarp is irregular but on the average about 4 or 5 feet high. It extends in an east-west line and is fairly distinct from the lower dune area. This red-sand area is relatively level and extends inland beyond the Elizabeth River. It is probably the Pamlico formation of the Pleistocene epoch.

About 500 feet from the scarp is the crest of the belt of high dunes. In back of the dunes the terrace is covered with scrub oak, pine, and in places swamp vegetation. Ponds and swamps occupy the depressions. Over almost all the area of the terrace in back of the dunes the ground is covered with a thin veneer of whitish material. Below

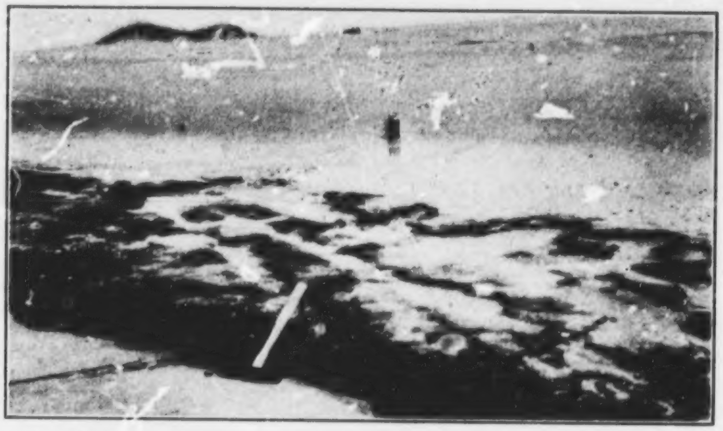

Exhibit 70.—Peaty stratum exposed at low tide on beach showing ground water seeping out just above the peat. High tide beach and first line of dunes in background

Exhibit 71.—Bluff of terrace in front of tool house and line of high dunes in back. In foreground are dune hillocks with sparse dune grass and depressions with heavier vegetation

Exhibit 72.--Area of experiment trench 600 in center background. Shows high dunes encroaching on scrub-oak forest

Exhibit 73.--Terrace and high dunes showing wells of 400 series

the whitish material are a few inches of blackish sand and below this the red sand. The whitish material probably consists of fine materials blown in by sea winds. The blackish sand contains organic material probably derived from vegetation.

Ponds and swamps.—On that part of the red-sand terrace that lies behind the belt of high dunes are many swamps and ponds. These ponds are from 6 to 8 feet deep and they do not always become dry in summer. Alligators are occasionally found in the larger ponds. Many of the ponds, when visited in May, 1922, were almost covered with lily pads and other aquatic vegetation. The swamp areas comprise thickets of low brush vegetation and scrub oak. The ponds are regarded as fresh-water ponds. An analysis of a sample from one pond showed only 38 parts per million of chloride. (Sample from No. 413, collected May 12, see p. 159.)

Elizabeth River.—Elizabeth River is a winding river channel in a wide marsh area. It is a part of a drowned river system and is affected by tides for at least 2 miles inland. The channel winds in close loops with many cut-offs. A fringe of marsh grass a few feet wide lies next to the river, and beyond, on both sides, is a wide stretch of reeds and rushes. The banks at the mainland are about 15 feet high, and except for a few inches of black sand on top show red sand throughout. The Elizabeth River is about at sea level and probably does not affect the ground water of the experimental area except as it may control the underlying salt water.

GEOLOGY

The geological formations comprise (1) the red-sand terrace formation which is probably the Pamlico of the Pleistocene epoch, and (2) the dune and beach sands and the peaty deposits of the swamps which are now forming and may be termed Recent.

Pamlico formation.—In the area under consideration the Pamlico formation consists chiefly of red sand grading below into brownish sand and probably underlain by a stratum of peaty material. The sand contains lenses of broken shell and blackish organic material. Well 217 is located on the high dunes and penetrates the recent blown sand for about 11 feet. At 12 feet there is a deposit of broken shells, indicating an old beach line. Below is reddish sand and at 18 to 22 feet there is brown sand. The well is 22 feet deep. Throughout the area behind the dunes the formation consists of a very thin coating of whitish blown sand underlain by a few inches of blackish sand. Below this is the red sand. The bank of the Elizabeth River shows red sand throughout (about 15 feet) with little blackish sand on top. The brown sand underlying the red sand is the water-bearing sand of well 217.

The peaty stratum that crops out at the mean tide line on the beach, and which is probably the same formation that is found at well 405 and at well 412, seems to underlie the area below the red and brown sand. The water table is just above this layer. Well 412 is entirely in the peaty material and draws water from this stratum. The stratum is probably very porous and contains much water, but does not yield its water freely to wells. It probably forms a nearly impervious stratum that controls the ground-water movement to a large extent.

Recent formation.—The Recent formations comprise beach sand, dune sand, and peaty materials now forming in the swamps. The dune sand is a white or gray quartz sand with a large amount of finely broken shell. It is constantly shifting with the wind and forms irregular dunes and depressions.

CLIMATOLOGICAL DATA

Climatological data are available for Southport, N. C., where a regular United States Weather Bureau observation station is maintained. Records of precipitation were also obtained at the experiment area and are given in Exhibit 75. Temperature and precipitation are of especial interest in connection with this investigation as they have a direct influence on the ground water.

Precipitation.—Exhibit 74 gives the monthly and the normal precipitation at Southport for 1921. Exhibit 41 shows the same graphically. The wide deviation of 1921 from normal is marked. Exhibit 75 gives the daily precipitation during May, 1922, for Southport and for the experimental area at Fort Caswell. The precipitation is discussed especially in connection with water levels. (See pp. 98–118.)

Exhibit 74.—*Temperature and precipitation at Southport, N. C.*

Month	Temperature		Precipitation	
	1921	Normal [1]	1921	Normal [2]
		° F.		*Inches*
January	49.2	47.2	8.78	3.70
February	50.8	48.6	4.17	3.86
March	62.3	53.8	3.54	3.62
April	64.8	61.9	6.58	2.93
May	67.7	71.0	7.38	3.28
June	77.8	77.4	2.32	4.56
July	79.7	80.3	16.02	6.35
August	80.0	79.7	4.90	5.68
September	81.6	75.3	1.14	4.56
October	65.9	66.2	4.64	4.45
November	61.4	56.6	2.43	2.59
December	51.4	49.1	1.79	3.51
Annual	66.0	63.9	63.69	49.09*

[1] Length of record, 67 years.

[2] Length of record, 45 years, cf. Exhibit 41.

Exhibit 75.—*Graph of monthly, 1921, and normal (based on 67 years) monthly temperature at Southport, N. C.*

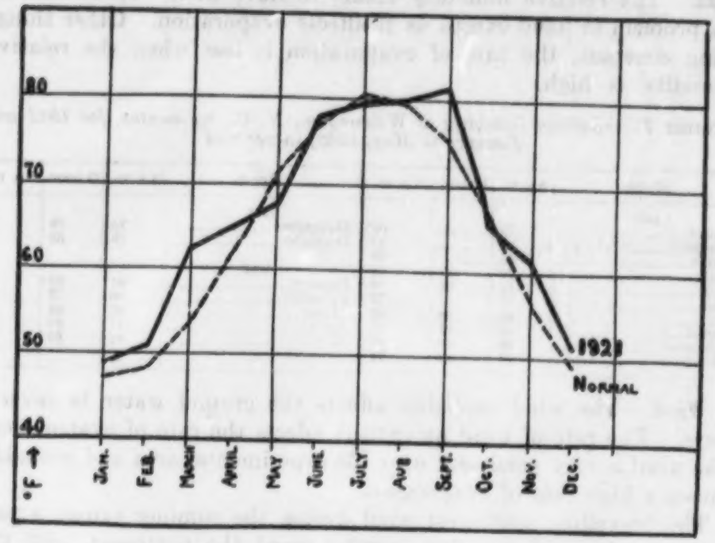

Exhibit 76.—*Daily precipitation in May, 1922, at Fort Caswell and at Southport, N. C. (in inches)*

Date	Fort Caswell	Southport	Date	Fort Caswell	Southport
1	0	0	18	0.19	0
2	0	0	19	0.17	0
3	0	0	20	0	0.40
4	0.26	0.29	21	0	0
5	0	0	22	0	0
6	0	0	23	0	0
7	0	0	24	0	0
8	0	0	25	0	0
9	0	0	26	0.66	0.45
10	0	0	27	(?)	1.30
11	0	0	28		0.79
12	0	0	29		0
13	0	0	30		0
14	0.34	0.23	31		T.
15	0	0	Month		6.88
16	2.12	0			
17	0	3.42			

Temperature.—Monthly temperatures for 1921 and normal monthly temperatures at Southport, N. C., are given in Exhibit 74, page 140. In Exhibit 75 page 141, the same data are shown graphically. In Exhibit 84, page 150, are given the daily temperatures for May, 1922, at Southport. The data in this table are discussed especially in relation to the temperature and movement of ground water and rate of evaporation. (See pp. 143, 149, 150, 167.)

Humidity.—Data on relative humidity are available for Wilmington, N. C. Exhibit 77 gives the relative humidity, by months, at 8 a. m., 12 noon, and 8 p. m., for 1921, and for January to May, 1922. The relative humidity seems to have little importance for the problem in hand except as it affects evaporation. Other things being constant, the rate of evaporation is less when the relative humidity is high.

Exhibit 77.—*Relative humidity at Wilmington, N. C., by months, for 1921 and January to May, 1922, in per cent*

Month	8 a. m.	12 noon	8 p. m.	Month	8 a. m.	12 noon	8 p. m.
1921				1921			
January	79	--------	80	November	85	59	80
February	[illegible]	--------	80	December	79	56	68
March	[illegible]	--------	78	1922			
April	79	57	73	January	81	69	77
May	81	61	76	February	86	72	82
June	78	56	77	March	80	60	73
July	84	66	85	April	77	62	74
August	85	64	81	May	82	60	80
September	86	56	80				
October	78	59	71				

Wind.—The wind probably affects the ground water in several ways. The rate of wind movement affects the rate of evaporation. The wind is very persistent over the experimental area and probably causes a high rate of evaporation.

The prevailing southwest wind during the summer causes a persistent shifting of the dune sand toward the northeast, and the shifting of the sand over the area causes slight changes in topography such as lowering of dunes and filling of depressions. Corresponding to these changes of topography there are probably changes in the shape of the water table. In the depressions there is considerable marsh grass and other vegetation which holds much of the sand that is blown into them. During the winter the wind often blows from the northeast and tends to blow the sand back.

The sea winds carry spray inland which deposits salt when it evaporates. This might account in part for the irregular distribution of chloride in the well waters.

Exhibit 78 gives the prevailing direction of wind at Southport, N. C., by months, for 1921 and January to May, 1922. The annual prevailing wind is southwest.

Exhibit 78.—*Prevailing wind direction, 1921, and January to May, 1922, Southport, N. C.*

Month	Wind direction	Month	Wind direction
1921		1921	
January	SW.	December	NW.
February	NE.	Year	SW.
March	SE.	1922	
April	SW.	January	NE.
May	SW.	February	SW.
June	SW.	March	SW.
July	S.	April	SW.
August	SW.	May	SW.
September	SW.		
October	NE.		
November	SW.	Annual	SW.

Evaporation.—Evaporation data applicable to this experiment are difficult to obtain. Probably the best that are available are the records of evaporation from a free water surface at Chapel Hill, N. C., beginning April, 1921. Chapel Hill is, however, more than 170 miles northwest of Southport, and has an altitude of 500 feet above sea level. Its mean annual temperature is 59° F., whereas that of Southport is 63.9° F., and its mean annual precipitation is 46.27 inches, whereas that of Southport is 49.09 inches.

Exhibit 79 gives the evaporation data by months for the period April, 1921, to May, 1922, and Exhibit 80 gives the data graphically for January, 1921 to May, 1922. Exhibit 81 gives daily evaporation and daily wind movement (in miles) at Chapel Hill for May, 1922, and Exhibit 82 shows the same graphically.

In the experimental area the conditions are unusually favorable for a large evaporation during the summer. The ground water is at a shallow depth and capillary action brings the moisture to the surface over a large part of the area. The air temperature is high, probably causing high temperatures in the soil and in the ground water. The winds are strong and persistent.

Referring to evaporation from land areas Meyer[1] (1917, 221) says: "The most important factor governing the rate of evaporation from land areas is the temperature of the air and of the moisture subject to evaporation." Also, "In general, the daily and monthly mean air temperature may be taken as the best available index to the mean rate of evaporation from land areas."

EXHIBIT 79.—*Monthly evaporation (in inches) at Chapel Hill, N. C., April, 1921, to May, 1922*

Month	Monthly evaporation	Month	Monthly evaporation
1921		1922	
April	2.69	January	0
May	3.32	February	1.10
June	4.59	March	2.97
July	5.15	April	3.82
August	5.45	May	4.49
September	4.47		
October	3.21		
November	1.49		
December	1.28		

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[1] Meyer, Adolph, Elements of Hydrology, p. 221.

Exhibit 80.—*Graph of monthly evaporation at Chapel Hill, N. C., and monthly temperature at Southport, N. C., January, 1921, to May, 1922*

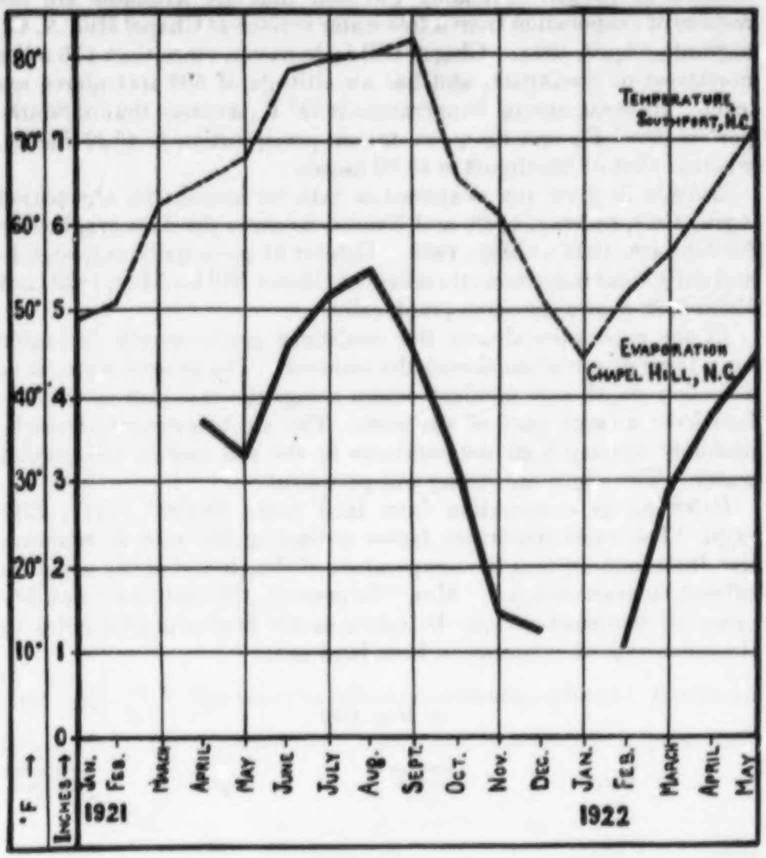

Exhibit 81.—*Daily evaporation and wind movement Chapel Hill, N. C., for May, 1922*

Day	Evaporation	Wind movement	Day	Evaporation	Wind movement
	Inches	*Miles*		*Inches*	*Miles*
1	0.154	20	18	0.066	7
2	.100	8	19	.168	35
3	.053	23	20	.196	16
4	.001	29	21	.161	11
5	.081	11	22	.164	17
6	.167	22	23	.170	20
7	.166	13	24	.246	24
8	.162	20	25	.192	22
9	.149	11	26	.137	14
10	.193	5	27	.106	23
11	.207	22	28	.181	63
12	.172	22	29	.170	21
13	.077	17	30	.231	20
14	.168	11	31	.112	19
15	.142	9			
16	.083	1	Month	4.469	562
17	.094	6			

Changes in air temperature cause changes in the rate of evaporation of ground water. It is said that, other things being equal, the rate of evaporation is approximately doubled for each 18° rise in temperature. C. H. Lee (1912, 54),[1] in connection with his experiments in Owens Valley, Calif., in evaporation, transpiration, and percolation, says:

> The rate of evaporation from soil depends on the temperature of the air and soil, the quantity of moisture already in the immediately surrounding atmosphere, the amount of moisture in the surface layers of the soil, and the character of the vegetation and other soil covering. The first two of these factors have the same effect on soil evaporation as on that from a free water surface—higher air and soil temperatures result in increased evaporation, as does also dryer atmosphere or increased movement of wind. * * *

While the actual amount of evaporation at the experimental area is not known, relative rates of evaporation can be approximated on the basis of variations in temperature. As there is a wide daily range of temperature there is probably also a wide daily range in the rate of evaporation, and the variations in the rate of evaporation probably have a very definite effect upon the water levels and the movement of the ground water.

It would be of value to install an evaporation tank to determine the amount of evaporation from the sand over the experimental area, as a detailed analysis of the movements of the ground water is impossible without such data. The movement of the ground water as shown by the uranin dye is being watched in detail. A study of the factors involved in the movement of the ground water indicate that evaporation is probably important. It is believed that data of evaporation from a free water surface are less important to the problem at hand than data of evaporation from the sand.

Transpiration.—Allied to evaporation is transpiration of moisture through plants. In the depressions there is considerable grass and marsh vegetation. In back of the high dunes and over most of the Red Sand terrace there is a growth of scrub-oak and other vegetation. The lower swamp areas are crowded with plants, and the ponds, when visited, were filled with lilies and other aquatic plants. All this vegetation causes loss of ground water through transpiration.

Lee (1912, 61) says that there is a marked periodicity in the rate of transpiration which investigators are led to believe is largely the result of varying intensity of light. Meyer (1917, 246) says, likewise, that transpiration is practically limited to the daylight hours. The difference in rate of transpiration at day and night must have an appreciable effect upon the ground water. Doubtless there are fluctuations of water level due to this diurnal variation in the amounts of ground water transpired. When transpiration is at its height there is probably a continual movement of water from the zone of saturation into the capillary fringe toward the roots of the plant. Evaporation involves a similar process but continues through the night at a rate determined primarily by temperature. When the dew point is reached evaporation stops.

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[1] Lee, C. H., 1912, An intensive study of the water resources of a part of Owens Valley, Calif. From U. S. Geol. Survey Water-Supply Paper, 294, p. 54.

It is the variation in amount of moisture transpired rather than the actual amount involved that is important to the problem in hand. The variation causes a variation in the condition and movement of ground water. During the day, about the time of maximum temperature, there is a maximum rate of transpiration, and this added to a maximum rate of evaporation from the sand must cause an appreciable capillary movement of ground water upward toward the surface.

During the summer, the ground-water level is doubtless depressed under the low areas by the large amount of evaporation and transpiration in these areas. The capillary fringe extends to the ground surface, and throughout the day moisture is continually passing from the zone of saturation to the atmosphere. During the night, evaporation and transpiration are small and the irregularities of the water table flatten out. Such changes affect the rate of movement of the ground water locally, or at least cause frequent minor changes in the ground-water levels.

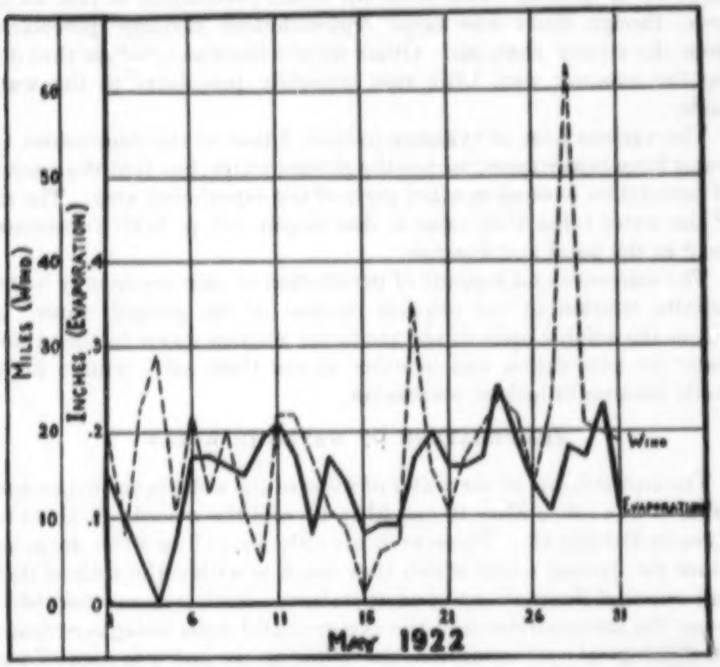
PERCOLATION

In relation to the fluctuation of the water table and the movement of ground water it is important to determine whether any rain that falls on the area percolates vertically from the surface to the ground water. In many places in the United States little or none of the rain reaches the ground water during the summer period, most of it being held in the upper few inches of soil and returned to the atmosphere by evaporation or through the transpiration of plants. In the area under consideration the water level in most of the wells rises after each rain, but it is uncertain whether the rise is due (1) to the direct percolation of rain water, (2) to the pressure of the absorbed rain water on the air that is confined in the interstices of the sand, transmitting pressure to the ground water, or (3) to hydraulic head from the pond and swamp area, which is an evident intake area. (See also p. 118.) The rise may be due to all three causes.

To test the amount of percolation two lysimeters were installed, one near trench 500 and the other near trench 600. The lysimeter used was a laboratory flask of 1 liter capacity with a glass funnel, in which was placed a filter paper and coarse sand with finer sand on top. The funnel had a diameter of about 3 to 3⅜ inches. This arrangement would allow water percolating downward through the soil to be caught in the flask, where it would be protected from evaporation.

Lysimeter No. 1 was buried just above the water table near trench 500. (See Exhibit 1.) It was located in a slight depression which showed evidences of being an area of active evaporation, and which was thought also to be an area of percolation. The water table stood about 3 feet below the surface when the lysimeter was put down on May 15. On May 16 there was a rain of 2.12 inches, on May 18 a rain of 0.19 inch, and on May 19, a rain of 0.17 inch. On May 24 the lysimeter was dug up and found full of water. The bottom of the flask was slightly above the water table, but it is possible that the water table had risen, flooded the flask, and then receded before the flask was dug up.

Exhibit 82.—*Graph of daily evaporation and wind movement, Chapel Hill, N. C., for May, 1922*



Lysimeter No. 2 was also installed on May 15. It was buried about 6 feet below the surface and about 2 feet above the water table. Immediately north and practically over the lysimeter was a 4-foot bank, so that there was really 10 feet of sand over it. It was dug up May 25 and found empty and dry, showing that no rain water had penetrated to it.

Much has been written on percolation of rain water to the zone of saturation. Lee (1912, 57), in connection with his experiments in Owens Valley, says:

> Even in a wet season percolating water does not penetrate to depths exceeding 2.5 feet unless more than 1 inch falls within a short period on moist soil. Even then it does not appear to reach depths greater than 4 feet.

Houk (1921)[3] concludes, from his Moraine Park experiments, "that during the summer months rain seldom percolates to such depths that it is not raised again by capillarity or by root action and evaporated or transpired back into the atmosphere." Lysimeter tests on Niles Cone, made by Bailey (1921, 95)[4] showed that there was no replenishment to the ground water from the direct percolation of rain on the cone, though there was large replenishment through percolation from the stream channels. Other writers likewise conclude that during the summer very little rain generally percolates to the water table.

The various lines of evidence indicated that in the depressions the water from heavy rains reaches the ground water, but that the amount of percolation is small in other parts of the experiment area. The rise of the water table after rains is due largely (cf. p. 118) to increased head in the pond and swamps.

The existence and amount of percolation of rain water may have a definite relation to the chloride content of the ground water. In places the soluble salts in the sands are washed down to the ground water by percolation and in other places these salts remain in the sands because of lack of percolation.

TEMPERATURE OF WATER IN WELLS

The temperature of the water of some of the wells in the experimental area was taken May 10 and May 12, and the records obtained are given in Exhibit 83. These wells are only about 3 to 5 feet deep, and hence the ground water which they reach is within the zone of daily and seasonal fluctuations of temperature. As it was not feasible to lower the thermometer into the experimental wells because of fear of bacteriological contamination, the following method was used: To get the temperature of water in one of the box observation wells a bottle was lowered into the well and was allowed to remain a few minutes after it had filled. The bottle was then raised and the thermometer placed in it and left until the mercury remained constant. Any possible error due to this method is thought to be negligible. In the case of the pipe wells water was pumped and then a bottle filled and the temperature of the water in the bottle observed.

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[3] Houk, Ivan, 1921, Rainfall and run-off in the Miami Valley. From Tech. Repts., pt. 8, State of Ohio, Miami Conserv. Dist., p. 19.

[4] Bailey, P., 1921, Engineering investigation of percolation from Alameda Creek and ground water studies on Niles Cone. From Biennial Report of the State Water Commission of California, 1919-20, Appendix E. pp. 95-105.

The slight variations in temperature shown by the records seem to be due chiefly to location in sun or shade. The differences in depths to water are too slight to be a factor in the differences of temperature. Wells 410, 411, and 412 are located in the scrub-oak area back of the dunes, where the ground is shaded, whereas the other wells are in areas heated by the sun. Records of the temperature of the water from wells 603, 604, and 605 are of doubtful value, as these are 2-inch pipe wells, and it is not certain that sufficient water was pumped to cool the pipe.

On May 10 the temperature of the air near well 409 varied according as the thermometer was held near the sand or high above it, indicating that a large amount of heat was reflected from the sand. The temperature of 76° F. was obtained a few feet above the sand. At Southport the maximum air temperature on May 10 was 80°, the minimum 58°, and the mean 69°. On May 12 the temperature of the air near the pond (No. 413) was 88° F., which was the same as that of the pond water.

Exhibit 83.—*Temperature of water in wells on May 10 and May 12, 1922*

Well No.	Depth to water table	May 10	May 12	Well No.	Depth to water table	May 10	May 12
	Feet	°*F.*	°*F.*		*Feet*	°*F.*	°*F.*
409	4.55	70	71	413	Pond.	....	[1] 88
406	5.07	71	71	503	2.75	71	72
405	4.95	71	72	504	4.40	70	71
404	2.96	71	73	505	3.98	72	72
403	4.72	71	....	506	5.40	71	73
402	5.26	69	70	603 [2]	2.53	....	73
401	4.96	....	71	604 [2]	8.20	....	72
410	5.24	64	66	605 [2]	6.80	....	72
411	4.06	66	....	Air temperature	....	[3] [4] 76	[5] 88
412	2.51	64	66				

[1] Exposed to sun's rays.
[2] Pipe wells. Pipes may not have been thoroughly cooled.
[3] Reflected heat from sand (?).
[4] Near 409.
[5] Near 413.

The air temperatures recorded at Southport on May 12 were maximum 84°, minimum 65°, and mean 74.5°.

In Exhibit 84 are given the maximum, minimum, and mean daily temperatures and daily range of temperature for May, 1922, at Southport, N. C. The experimental area lies in the sand dune belt and is exposed to the direct rays of the sun. Hence, the maximum temperatures may be a little higher and the minimum temperatures a little lower than at Southport. Monthly temperatures for 1921 and normal monthly temperatures at Southport are given in Exhibit 74.

It is believed that daily and seasonal differences of temperature of the ground water are sufficient to have an appreciable effect on the rate of movement of ground water and therefore probably also on the movement of bacteria. Referring to rate of transmission of water through sand, Slichter (1905, 13) says:[4]

> It should be borne well in mind that the rate of transmission varies very greatly with the temperature of the water. For example, a change from 50 to 60° increases the capacity to transmit water under identical conditions by about 16 per cent, while a change from the freezing temperature to a temperature of 75° will nearly double the power of a soil to transmit water. This difference, of course, is not due to any change in the soil itself, but is due solely to the increased ease with which water flows at high temperatures compared to the ease with which it flows at low temperatures.

In computing the rate of flow of ground water at trench 500 in May, 1922 (see p. 167), 71° F., the average air temperature at Southport for May, 1922, was used as the average temperature of the ground water. In May the temperature of the ground water is doubtless slightly lower than the mean air temperature, but, on the other hand, the air temperatures at the experiment area are probably somewhat higher than those at Southport.

Another effect of variation of air temperatures, and, hence, of ground-water temperatures, is the change in capillary attraction of the ground water, which may cause fluctuations of water levels in wells. Veatch (1906, 55) says:[5]

> A rise in temperature, by decreasing the capillary attraction, causes some of the capillary water above the water table to be added to the zone of complete saturation, and so increases the level of the water in wells. Conversely, a decrease of temperature by increasing the surface tension and capillary attraction, causes water to be transferred from the ground water to the partially saturated zone above it, and so lowers the water in wells. There is, then, a continual interchange, a flux and reflux, between the ground water and the water in the partially saturated zone above it.

EXHIBIT 84.—*Maximum, minimum, mean daily temperatures, and range of daily temperature, May, 1922, Southport, N. C.*

Date	Maximum	Minimum	Mean	Range	Date	Maximum	Minimum	Mean	Range
1	75	55	65	20	18	76	63	69.5	13
2	74	56	65	18	19	78	65	71.5	13
3	82	62	72	20	20	82	68	75	14
4	80	58	69	22	21	86	69	77.5	17
5	75	57	66	18	22	89	65	77	24
6	74	58	66	16	23	85	68	76.5	17
7	76	58	67	18	24	80	67	73.5	13
8	79	59	69	20	25	82	72	77	10
9	76	62	69	14	26	78	71	74.5	7
10	80	58	69	22	27	84	70	77	14
11	80	64	72	16	28	72	57	64.5	15
12	84	65	74.5	19	29	75	51	63	24
13	89	68	78.5	21	30	79	65	72	14
14	85	65	75	20	31	78	69	73.5	9
15	80	64	72	16					
16	78	60	69	18	Month	79.6	62.9	71.25	16.7
17	78	60	69	18					

Maximum range, 24° (29 and 22); minimum range, 7°; mean range, 17°.

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[4] Slichter, C. S., 1905, Field measurements of the rate of movement of underground waters. From U. S. Geol. Survey Water-Supply Paper 140.

[5] Veatch, A. C., 1906, Fluctuations of the water level in wells, with special reference to Long Island, N. Y.: U. S. Geol. Survey Water-Supply Paper 155

SOIL MOISTURE

In the zone between the surface and the water table there is a certain amount of moisture held chiefly by molecular attraction. Part of this moisture is in equilibrium with the moisture of the atmosphere and will not evaporate at ordinary temperatures though it can be driven off by heat. The soil-moisture content differs from place to place and at different depths and varies with the weather. For the purpose of these experiments, the soil-moisture content indicates something of the variations in the soil and it may affect the movement of uranin dye and bacteria.

Several series of soil samples were tested for moisture content. Doctor Eaton took two series, one at well 116 and one at well 216 in December, 1921, when the wells were put in. On May 17, 1922, immediately after a rain of 2.12 inches, samples were taken by the writer near trench 500, trench 600, and well 503. At each of these three places samples were taken 6 inches below the surface and at each succeeding 6 inches, down to the water table. The lowest sample was usually taken a little above the water table. Plans to take a similar series in a dry period could not be carried out in the time allotted.

Samples of series 1 were taken near trench 500, where samples were also taken for porosity tests and mechanical analyses and where lysimeter 1 was buried. The materials encountered were: Surface to 6 inches, gray dune sand; 6 to 8 inches, blackish sand; 8 inches and below, brownish sand. The moisture content is given in Exhibits 85 and 86.

Samples of series 2 were taken near trench 600, where samples were also taken for porosity tests and mechanical analyses and where lysimeter 2 was buried (see Exhibit 1) Red sand was encountered throughout. The moisture content is given in Exhibits 85 and 86.

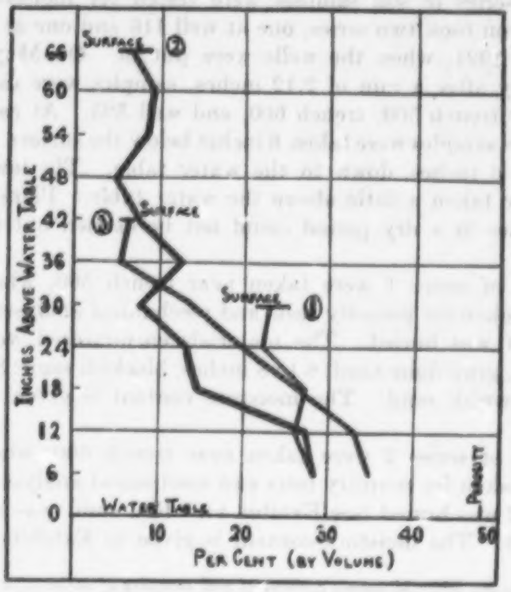
EXHIBIT 85.—*Moisture content of soil samples of series 1, 2, and 3*

Depth	Percentage of moisture					
	Series 1		Series 2		Series 3	
	By weight	By volume	By weight	By volume	By weight	By volume
6 inches	16.7	23.0	5.0	6.9	4.8	6.6
12 inches	16.1	22.2	6.6	9.1	3.8	5.2
18 inches	19.8	27.3	6.2	8.6	10.0	13.8
24 inches	18.9	26.1	3.6	4.9	14.3	19.7
30 inches	20.7	28.6	5.6	7.7	19.6	27.0
36 inches			9.3	12.8	24.1	33.3
42 inches	....	....	5.8	8.0	25.3	34.9
48 inches	....	....	9.8	13.5	....	....
54 inches	....	....	10.6	14.6	....	....
60 inches	....	....	19.6	27.0	....	....
66 inches	....	....	20.7	28.6	....	....

Samples of series 3 were taken from near well 503, about 200 feet from the mean high-tide line and 100 feet from trench 500. The materials encountered were gray dune sand from the surface to about the water table, where black peaty material was found. The moisture content is given in Exhibits 85 and 86.

The method used was as follows: Borings were made with a soil auger and samples were taken at specified depths; the samples were placed in air-tight bottles and taken to the laboratory, where they were weighed and put in an oven to dry; several weighings were made during the drying until the weights were constant. To obtain the percentage of moisture by weight the loss in weight was divided by the weight of the dry sample; to obtain the percentage of moisture by volume the percentage by weight was multiplied by the specific gravity of the dry sample.

Exhibit 86.—*Graph of moisture content of soil samples of series 1, 2, 3, in percentages by volume*



Following are descriptions of samples on which tests of soil moisture were made by Doctor Eaton in December, 1921. The moisture contents are given in Exhibit 87 and are graphically shown in Exhibit 88.

SOIL SAMPLES FROM WELL 118

Surface: Brownish gray sand, with a few white and black specks.
1 foot: Same as surface, with a few more black specks.
2 feet: Same as at 1 foot.
3 feet: Finer grained and cleaner, with fewer white and black specks.

4 feet: Same as at 3 feet, with many large black particles and a few white ones.
5 feet: Reddish sand, even, occasional large black specks.
6 feet: Same as at 5 feet.
7 feet: Same as at 5 feet.
8 feet: Same as at 5 feet.
9 feet: Same as at 5 feet.

SOIL SAMPLES FROM WELL 216

Surface: Coarse brownish gray sand, with large particles of shell and a few black specks.
1 foot: Moist brownish sand, with few black specks, without shells.
2 feet: Same.
3 feet: Same.
4 feet: Same, with fewer black specks.
5 feet: Same as at 4 feet.
6 feet: Same.
7 feet: Same.
8 feet: Dark lumpy sand, finer in grain.
9 feet: Fine red sand.
10 feet: Same as at 9 feet.
11 feet: Same.
12 feet: Same.
13 feet: Same.
14 feet: Very wet sand similar to that at 13 feet.

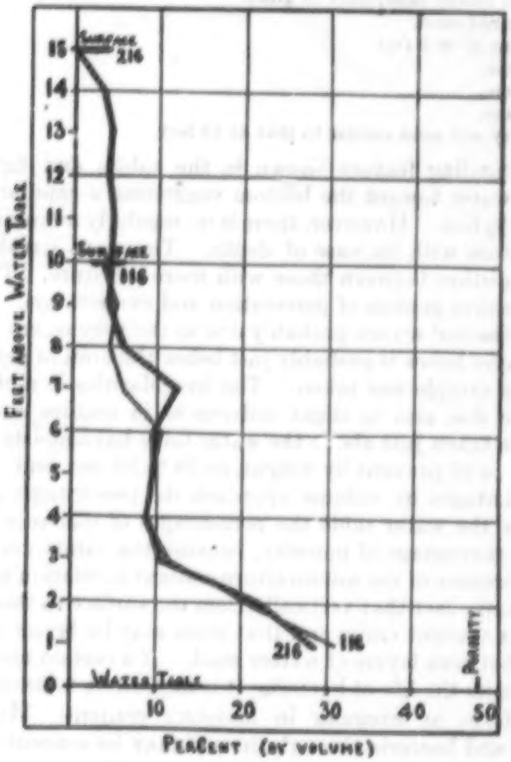
The outstanding feature shown in the tables and figures is the increase of water toward the bottom suggesting a capillary fringe of about 2 to 2½ feet. However, there is no regularly increasing amount of soil moisture with increase of depth. There are streaks or strata with less moisture between those with more moisture. This may be due to successive periods of percolation and evaporation. The moist layers near the surface are probably due to the very recent rain. The less moist layer below is probably just below the limit of percolation at the time the sample was taken. The irregularities in moisture may, however, be due also to slight differences in texture and porosity. The samples taken just above the water table have moisture contents of about 21 to 25 per cent by weight, or 29 to 35 per cent by volume. These percentages by volume approach the percentages of porosity. At or below the water table the percentages of moisture by volume express the percentage of porosity, because the sands are saturated.

The importance of the soil-moisture content in relation to the experiment lies in the fact that vertically from the surface to the water table the moisture content varies and that there may be layers or streaks of drier sand between layers of wetter sand. If a certain amount of soil moisture limits the life of bacteria, it is important to know whether a soil is uniform or irregular in moisture content. Movement of uranin dye and bacteria through the soil may be concentrated in the layers which have greater moisture content. This variability within a few inches of the moisture content of the sands may in part explain the 2-inch layer of uranin-dyed soil in the capillary fringe at the 500 trench. (See p. 26.)

Exhibit 87.—*Moisture content of soil samples from well 116 and well 216*

Depth	Percentage of moisture				Depth	Percentage of moisture			
	Well 116		Well 216			Well 116		Well 216	
	By weight	By volume	By weight	By volume		By weight	By volume	By weight	By volume
Surface	2.64	3.6	0.92	1.3	8 feet	15.14	20.9	8.98	12.3
1 foot	3.50	4.5	2.55	3.5	9 feet	22.07	30.5	7.09	9.7
2 feet	3.21	4.4	3.03	4.2	10 feet			6.20	8.5
3 feet	4.28	5.9	2.79	3.9	11 feet			6.40	8.8
4 feet	7.43	10.3	3.34	4.6	12 feet			7.54	10.4
5 feet	6.94	9.6	3.35	4.6	13 feet			15.76	21.7
6 feet	6.42	8.9	3.36	4.6	14 feet			20.65	28.5
7 feet	8.20	11.3	4.20	5.8					

Exhibit 88.—*Graph of moisture content of soil samples from wells 116 and 216, in percentages by volume*



POROSITY

Materials.—Porosity tests were made on samples of sand taken near the 500 and 600 trenches and are typical of the materials obtained in these trenches. Where the samples were taken near trench 500 the section is as follows: (1) Gray beach or dune sand from the surface to about 6 inches, (2) blackish sand from about 6 inches to 8 inches, grading into (3) brownish sand below. Near the 500 trench the materials are variable, but the general order of gray dune sand, blackish peaty material, with brownish sand below, is found in most places. At the 600 trench the material is red sand from the surface to the depth sampled.

Method.—To obtain the porosity the formula, $P=100\ \frac{S-a}{S}$ was used, in which P is the porosity, S the specific gravity of quartz comprising the sand grains, which was taken as 2.65, and a the specific gravity of the dry sample. To obtain the specific gravity of the dry sample a known volume of the sand was dried in an oven until it became constant in weight. In obtaining the sample a 600-cubic centimeter cylindrical can with sharp edge was pushed into the vertical side of a pit or trench dug for the purpose until the bottom of the can was even with the bank. Then the sand around the can was dug away and the can was taken out, filled to the top.

Porosity data.—The porosities obtained are as follows, expressed as a percentage of the total volume of the material.

	Per cent
Near trench 500:	
Gray dune sand	46.0
Blackish sand	48.3
Brownish sand	48.7
Near trench 600:	
Red sand	49.4
Average	48.0

The following table taken from a summary of porosities of rocks by M. L. Fuller (1906, 61)[6] gives data for comparison based on tests of many samples:

Material	Authority	Porosity in per cent of total volume		
		Minimum	Maximum	Average
Sand (uniform)	King[1]	26	47	35
Sand (mixture)	King	35	40	38
Clay	King	44	47	45
Soils	U. S. Dept. Agriculture	45	65	55

[1] U. S. Geol. Survey Ann. Rept. 19, Pt. II, 1898, pp. 209-215.

Meinzer (1923,[2] p. 8) says:

> The porosities of different materials range from only a small fraction of 1 per cent to more than 50 per cent. Most of the newly deposited material of the Mississippi delta has porosities of 80 to 90 per cent. Porosities of more than 40 per cent are, however, rare except in soils and in recent deposits that have not had time to settle. A porosity of less than 5 per cent may be regarded as a small porosity; one between 5 and 20 per cent as a medium porosity, and one greater than 20 per cent as a large porosity.

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[2] O. E. Meinzer, 1923, The Occurrence of Ground Water in the United States, with a discussion of principles. From Water-supply Paper 489, United States Geological Survey.

[6] Fuller, M. L., 1906, Underground-water papers: U. S. Geol. Survey Water Supply Paper 160.

The high porosities of the Fort Caswell materials are due to the uncompacted character of the sands and the relative uniformity of size of grain or high degree of assortment.

MECHANICAL ANALYSES

Five samples of soil were obtained for mechanical analysis. They were practically duplicates of those obtained for the porosity tests. Sample 1, taken at the surface near trench 500, is typical of the gray dune sand; sample 2, taken 6 to 8 inches below the surface, is typical of the layer of dark blackish sand; sample 3, taken 14 inches below the surface, is typical of the brownish water-bearing sand; sample 4, taken near the southeast end of trench 500, at 3½ feet below the surface, is a black peaty soil, from which it is difficult to obtain water; sample 5, taken near trench 600, about 10 inches below the surface, is typical of the soil at the 600 trench experiment.

The samples were sent in glass jars to the laboratory of the Geological Survey in Washington, D. C. At the laboratory a small sample of the air-dry material was obtained by halving, using a sampling dish. The small sample was weighed, put in the top of a nest of sieves, and shaken in a mechanical shaking machine for 15 minutes. The residues in the several sieves were weighed and these weights expressed in percentages of the total weight of the small sample, are given in Exhibits 89 and 90.

EXHIBIT 89.—*Mechanical analyses of sands from the experimental area at Fort Caswell, N. C. (in percentages of the total weight of the sample)*

	Diameter millimeters	Sample number				
		1	2[1]	3	4[1]	5[1]
Fine gravel	2 to 1	0.24	0.28	0.10	0.30	0.11
Coarse sand	1 to 0.5	5.10	4.31	3.66	5.04	4.23
Medium sand	0.5 to 0.25	41.19	32.08	33.78	32.99	36.75
Fine sand	0.25 to 0.125	51.62	58.72	59.33	56.18	56.36
Very fine sand	0.125 to 0.074	1.78	2.28	1.15	2.52	1.23
Silt	Less than 0.074	.07	2.07	1.98	1.75	1.06
Effective size of grain (mm.)[2]		.14	.13	.13	.13	.14
Uniformity coefficient[3]		2	1.9	1.9	1.9	1.9
Porosity (per cent)		46	48.3	46.7		49.4

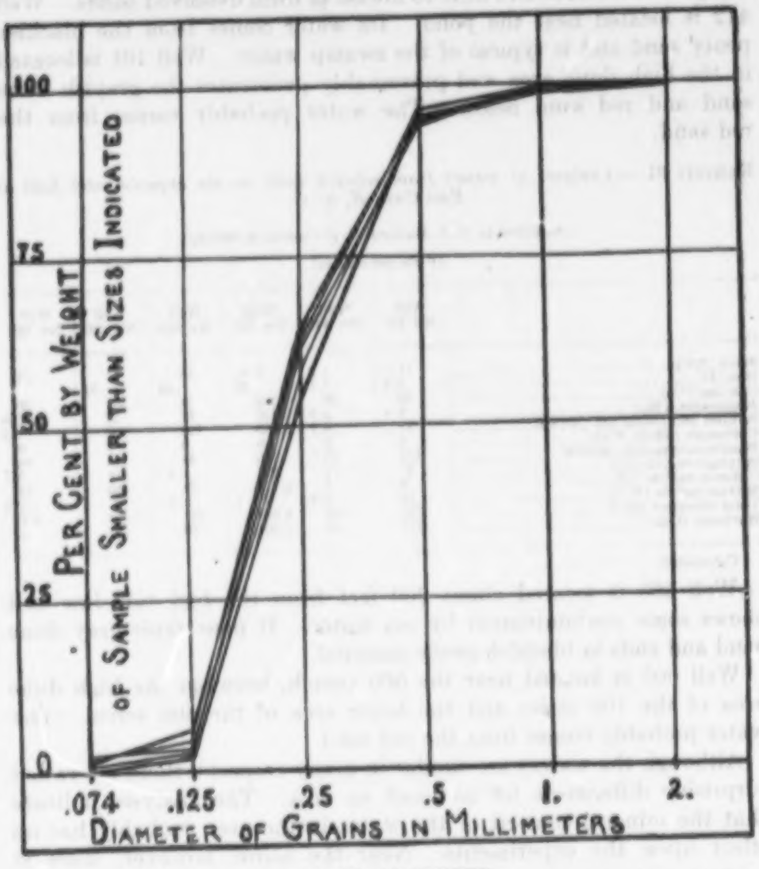
[1] No. 2 had 0.22 per cent greater than 2. mm.; No. 4 had 0.03 per cent greater than 2. mm; No. 5 had 0.04 per cent greater than 2. mm.

[2] Based on method of Hazen. Figures taken from curve in Exhibit 90. The diameter of a grain that is just larger than the grains comprising 10 per cent of the sample by weight.

[3] The uniformity coefficient is obtained by dividing the diameter of a grain that is just larger than the grains comprising 60 per cent of the sample by the effective size of grain as above defined.

The terminology of the Bureau of Soils has been used except that 0.125 millimeter and 0.074 millimeter for the upper limits of very fine sand and of silt, respectively, are used instead of 0.1 millimeter and 0.05 millimeter. As there is very little clay in these samples it was not separated from the silt, all material finer than 0.074 being classed as silt. There was very little organic matter except a few roots and pieces of wood, which usually remained on the 2-millimeter or 1-millimeter sieve. The results obtained from the analyses are considered sufficiently accurate for the present purpose. All five samples are similar in mechanical composition. They are all medium to fine, well-assorted sands.

Exhibit 90.—*Graph of mechanical composition of soil samples*



WATER ANALYSES

Complete analyses.—Analyses of the mineral content of water from six of the wells were made in the water resources laboratory of the Geological Survey, the results of which are given in Exhibit 91. The data in regard to the wells are given on page 158, and the location of the wells is shown in Exhibit 1.

Well 409 is located near the high-tide line and the water comes from the gray beach and dune sand. The water shows contamination with sea water. The chloride determinations of other samples from this well also indicate a tidal effect by variation in amount of chloride as well as high chloride content. (See Exhibit 92.) Well 401 is located midway between the beach and the pond and the water comes from the red sand. Its water is the lowest of the six samples in chloride and next to lowest in total dissolved solids. Well 412 is located near the pond. Its water comes from the blackish peaty sand and is typical of the swamp water. Well 101 is located in the high dune area and presumably penetrates the grayish dune sand and red sand below. The water probably comes from the red sand.

Exhibit 91.—*Analyses of waters from selected wells on the experimental field at Fort Caswell, N. C.*

(Analyzed by C. S. Howard, U. S. Geological Survey)

[Parts per million]

	Well No. 101	Well No. 401	Well No. 409	Well No. 412	Well No. 503	Well No. 605
Silica (SiO_2)	11	1.3	2.8	18	11	11
Iron (Fe)	3.4	4.1	.58	.62	.34	14
Calcium (Ca)	40	29	362	18	101	29
Magnesium (Mg)	5.9	2.3	195	12	23	1.8
Sodium and potassium (Na+K)	12	6.1	1,080	[1] 28	403	7.2
Carbonate radicle (CO_3)	0	0	0	0	0	0
Bicarbonate radicle (HCO_3)	111	86	170	44	286	46
Sulphate radicle (SO_4)	27	12	377	7.4	11	9.7
Chloride radicle (Cl)	8	6	2,210	78	680	12
Nitrate radicle (NO_3)	16	5.2	T.	1.6	T.	2.4
Total dissolved solids	195	112	4,628	317	1,600	106
Hardness (Calc.)	124	82	1,204	94	347	57

[1] Calculated.

Well 503 is located about 200 feet from the high-tide line and shows some contamination by sea water. It penetrates gray dune sand and ends in blackish peaty material.

Well 605 is located near the 600 trench, between the high dune area of the 100 series and the lower area of the 500 series. The water probably comes from the red sand.

Although the waters are similar in many respects, there are rather surprising differences for so small an area. The analyses indicate that the mineral content of the water in the area probably has no effect upon the experiments. Near the shore, however, there is evident contamination with sea water (cf. p. 65, 73).

Chloride content.—Chloride determinations were made for a few samples from a number of the wells. The data obtained are given in Exhibit 92 and are shown graphically in Exhibit 93. The number of tests was not sufficient to draw detailed conclusions, but was adequate to indicate that the chloride content does not constitute a serious problem in the present investigation. To make a complete survey of the chloride content of the water, samples should be taken from all the wells at different seasons, before and after rains, at high and low tides, and probably at half and quarter tides.

The data obtained indicate that the distribution of chloride is somewhat irregular, but that in general there is a decrease in the amount of chloride with distance from the ocean. Near the shore the ground water is evidently contaminated with sea water. In general there was less chloride in the May 17 samples than in those of May 12, due to the heavy rain on May 16 and 17.

EXHIBIT 92.—*Chloride content of samples from wells*

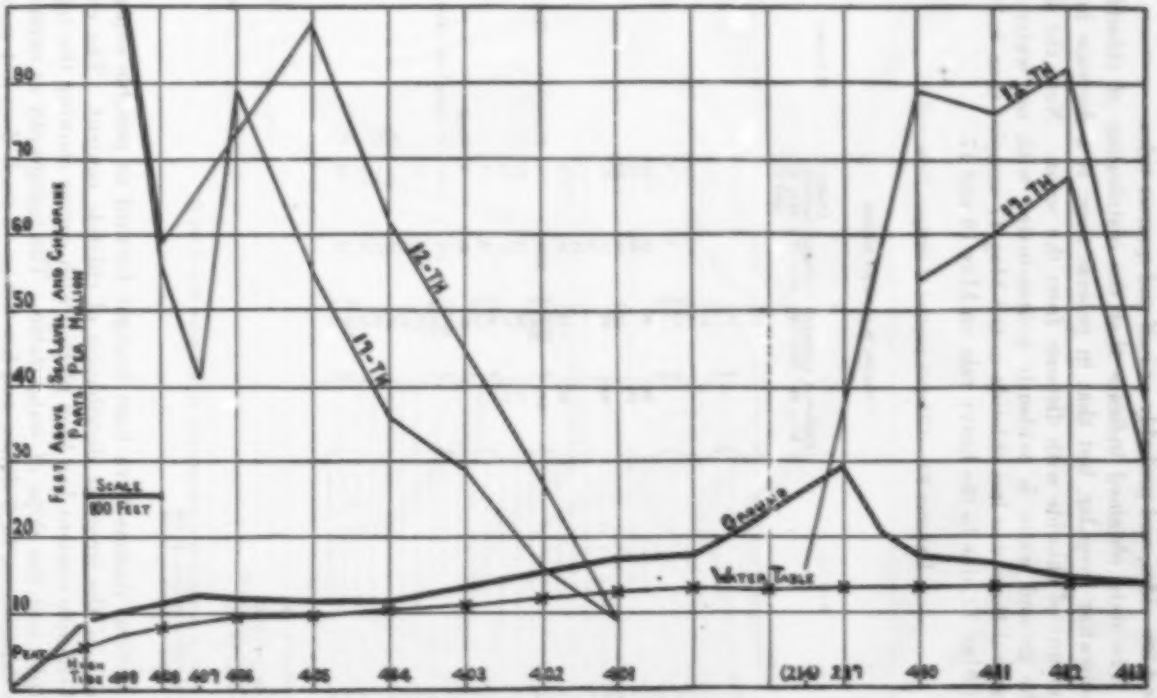
Well No.	Chloride, in parts per million				Remarks[1]
	Collected May 10	Collected May 12	Collected May 17	Change between May 12 and 17	
101	....	[2] 8	....	....	
101		11			
214	....	16	....	....	
316	....	8	....	....	
401	....	[2] 8	9	0	
401		9			
402	28	28	16	−12	
403	63	....	39	−24	
404	....	62	36	−26	
405	(?)	88	55	−33	
406	....	....	79	....	
407	....	....	41	....	
408	45	[3] 80	56	−3	
409	405	2210	2370	−110	Probable tidal effect.
409		[illegible]			
410	74	79	54	−25	
411	75	76	60	−16	
412	....	[3] 78	66	−14	
412		52			
413	....	38	30	−8	Pond
503	....	780	192	−466	Probable tidal effect.
503		536			
504	....	120	96	−83	
505	....	43	32	−11	
506	....	26	37	+11	(?).
603	....	18	21	+3	(?).
604	....	52	50	−2	
605	....	[3] 12	13	+2	(?).
605		11			

Beach pool	18,742
Sea	18,584
Rain (sea storm)	4.2
Rain (inland storm)	5.0
Average for sea	19,380

[1] Rain: 0.28 inch May 4; 0.34 inch May 14; 2.12 inches May 16 and 17.
[2] Complete analysis, p. 158.
[3] Complete analysis, p. 158.

Several reasons have been brought forward as possible explanations of the irregular distribution of chloride content. The curve of chloride content has been plotted with curves showing the topography and the slope of water table. The topography as expressed in depressions, high dunes, and low dunes, in itself does not seem to be a determining factor. The water table slopes from the pond to the sea and does not seem to affect the chloride content. Depth to water,

Exhibit 93.—*Graph of chlorine content of water in 400 set, May 12 and 17, 1922, with topography and depth to ground water*



which involves distances small enough for capillarity and evaporation may be a contributive factor. In areas where ground water is sufficiently near the surface for evaporation to be continual there may be a concentration of chloride. However, the curves show that this is by no means the chief causal factor. Depth to water which involves large distances where there is no percolation of rain water and short distances where there is possible and probable percolation may be another factor. Where percolation of rain vertically to the zone of saturation takes place there is a leaching of soluble salts from the sand and a possible concentration of salt and other mineral content in the ground water of these areas. It is believed that there are areas in which rain water reaches only a few inches below the surface, and there are also areas where rain water percolates to the ground water. Percolation then may be a contributive factor to the irregularity of the distribution of chloride.

The kind of material in which the ground water occurs seems to be of no importance in this connection. The line separating the red-sand area from the gray dune-sand area does not seem to mark any difference in chloride content of the ground water. Some of the samples of sand collected for mechanical analysis were tested for chloride content, but all the samples showed less than 0.005 per cent of chloride.

It was thought that the water in the beach pool (see Exhibit 1) located in the outcrop of peaty material (Exhibit 69) would show a very low chloride content. At this point it is believed that the water table crops out and ground water is seeping out. However, the one determination indicates a very high chloride content, higher even than the chloride content of actual sea water a few yards distant but lower than the chloride content of an average sea water (19,350 parts per million for 35 per cent salinity). This high chloride content may be due in part to concentration caused by evaporation and in part to the seeping out of contaminated water from the near shore area. Well 409 and well 303 showed high chloride content indicating sea water contamination (cf. also p. 73).

Two samples of rain water from the rain gauge were tested. The rain water from a supposed sea storm contained 4.2 parts per million of chloride, while that from a supposed inland storm contained 8 parts per million of chloride, or almost double the amount. The data are not sufficient for general conclusions. The rain on May 14, the supposed inland storm, was 0.34 inch, the chloride content was 8 parts per million. The rain on May 16, the supposed sea storm, was 2.12 inches; the chloride content was 4.2 parts per million. It is possible that salt had been deposited on the gauge by spray prior to May 16.

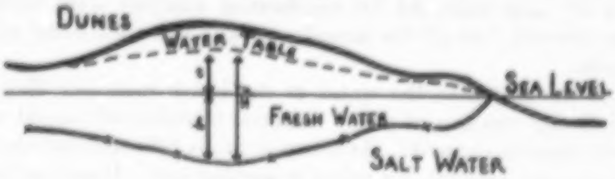
It is suggested that the height of the tide at the time of taking the chloride sample may be important. On May 17, when the samples were taken, it was recorded that the tide was falling, but near high.

No record is available for May 12. On May 10 the tide was reported as approximately low. The time elapsing during the process of taking samples may have been sufficient to involve some tidal effect. Often there were several hours between the collecting of the first and last sample of the series, and during this time the tide may have changed sufficiently to cause a difference in the degree of sea-water contamination.

Plotted curves showed that at high tide there is probably a reversal of slope of the water table near shore. The change of slope from that of low tide to that of high tide and back may be so gradual, however, that the gradient of the water table is merely lessened for some distance back from shore, and there is no actual reversal of the gradient. More data are necessary, however, before any definite statement can be made.

The importance of the chloride problem seems to be in the possible effect of high chloride content of the water near shore on the movement of the ground water at the uranin experimental areas. Actual chloride content of 680 parts per million on May 12 at well 503 may affect the movement of the ground water, and conceivably might affect the life and motility of bacteria. It certainly shows contamination of sea water, and hence may indicate a reversal of the slope of the water table (cf. p. 73). On May 17 the same well showed a chloride content of 192 parts per million, indicating much lower sea water contamination. There seems to be a tidal effect in this well which must affect the ground-water movement. This well is about 100 feet from the 500 trench and is the place toward which the water table presumably slopes.

Exhibit 94.—*Diagram illustrating Herzberg's theory of sea-water contamination (after Brown)*



Near the ocean the water in wells is often contaminated by sea water. Data have been collected on this subject and are presented in a report entitled "A study of coastal ground water with special reference to Connecticut," by J. S. Brown, 1925. The general theory, called Herzberg's theory, is essentially this: Salt water underlies the fresh ground water at a depth which is a function of the height of the water table above sea level. (See Exhibit 94.) The contact between fresh and salt water is not sharp and is probably a zone.

The wells in the experimental area are all shallow and usually are only about one-half to one foot below the water table. Therefore, they are probably not affected by sea-water contamination, as expressed by Herzberg's theory. The fact that wells 409 and 503 show undoubted contamination by sea water at distances of 50 and 200 feet from extreme high-tide level indicates that there may be contamination at the water table at certain distances inland. While the Herzberg theory does not seem to be operative in this case, more complete data on the contamination in this area may modify or expand the present theories of sea-water contamination.

WATER LEVELS

Water table [1].—While the general slope of the water table is from the pond to the beach, this slope is neither regular (on a given day) nor absolutely uniform at different times. One set of readings (May 22 and 24, 1922) showed that along the line of the 400 wells (Exhibits 1 and 57) the slope from well 412 to the beach was about 13.5 feet in 1,350 feet, or 1 per cent. From well 412 to well 401 the slope was gentle, about 1 foot in 450 feet, or 0.2 per cent; from well 401 to well 406 the slope was steeper, about 1 foot in 150 feet, or 0.7 per cent; from well 406 to well 409 the slope was steeper still, about 1 foot in 75 feet, or 1.3 per cent; from well 409 to the beach where the ground water seeps out the slope was steepest, about 1 foot in 21, or 4.7 per cent. These changes in gradient in the ground water slope indicate that possibly the permeability of the sands may not be as uniform as the tests indicate. However, there may be percolation of rain in the depressions which would account for the different gradients.

Near the group of wells 300 there seemed to be a slope of the water table toward the southeast. Near wells 604 and 605 there was a steep slope toward the southeast. Also near well 603 there was a fairly steep slope south and southeast. These southeast slopes were expected to have a decided influence on the direction and rate of movement of the uranin dye at the 600 experiment, but eventually the uranin moved slightly southwest. (See Exhibit 1.) Near the 500 series, especially near well 503, there is a southwest slope of the water table. This slope probably controlled the southwest movement of the uranin dye at the 500 experiment. These differences in direction and gradient of the slope of the water table involve corresponding differences in direction and rate of movement of the ground water. A simple movement of ground water from pond to beach does not hold. There are minor local changes which need to be considered especially in relation to the uranin experiments.

The shape of the water table probably changes considerably from dry season to wet. With uniform conditions as respects rainfall, it is certain that during the summer season the water table is lowered considerably (see, however, p. 108), but if there is much rain during the summer there may be a fluctuation rather than a steady lowering of the water table. A radical change in the contour of the water table may mean radical changes in the direction and rate of movement of the ground water at the experimental trenches.

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[1] This portion of Doctor Stearns' report has been condensed and abridged, as the data are considered elsewhere in the bulletin in connection with additional data procured later.—C. W. S.

Areas of intake and discharge.—In general, the chief area of intake is the pond, swamp, and low area in back of the high dunes. Over most of this area it is believed the water from rain and snow percolates downward to the zone of saturation. In addition, there are probably small areas of intake in the depressions among the dunes. It is believed that in these depressions rain water percolates to the ground water. (See pp. 146.) However, the lysimeter test made was inadequate and a definite statement can not be made. It is believed also that on the experiment area exclusive of the depressions percolation is in general reduced in summer.

In general, the chief area of discharge is along the peaty layer on the beach where ground water can be seen, at low tide, seeping out. In addition, the depressions are areas of discharge through evaporation. These areas are doubtless areas of intake during and immediately after a rain; at other times they are areas of evident evaporation and hence discharge. Besides evaporation, from the ground, of moisture brought to or near the surface by capillarity, there is a large amount of moisture transpired through plants. The depression areas contain much grass and marsh vegetation, and the amount of moisture transpired through this vegetation must be large. Likewise in the scrub-oak and swamp areas on the terrace in back of the high dunes there is much plant life, and hence a large amount of transpiration.

Quantitative statements of amounts of precipitation percolating to the ground water and of ground water discharged through seepage, evaporation, and transpiration of plants can not be given. The amounts of moisture transpired through plants and the amount of ground water seeping out on the beach, are difficult to measure. Probably only approximations of these could be obtained. Such data would aid materially in the determination of the fluctuations of the water levels and hence of the movement of the ground water in relation to the experiment in hand.

Fluctuations of water levels.—Records of depth to water in the 400, 500, and 600 wells were obtained. The data for April 18–May 24, 1922 are given in detail in Exhibit 95 p. 165 as elevations of water table above sea level and are shown graphically in Exhibit 55. Levels were run to all the observation wells and temporary holes, and determinations made of height above sea level of the bench mark at the well. Depths to water were measured with a steel tape. The measurements made May 22 and 24 were used as a base for the contour map of the water table. Measurements made on May 17 were used for the curve Exhibit 93, which is plotted with the curve of the chloride content of the water samples collected May 17.

EXHIBIT 95.—*Elevations of water tables at various dates, April 18–May 24, 1922*

[Feet above mean low tide]

Well No.	Apr. 18	Apr. 19	Apr. 20	Apr. 22	Apr. 24	Apr. 27	May 1	May 10	May 15	May 17	May 18	May 19	May 20	May 22	May 24
409	....	6.87	6.79	6.66	6.59	6.74	7.07	7.02	7.02	7.64	7.68	7.52	7.31	6.94	....
408	....	7.63	7.58	7.47	7.39	7.37	7.72	7.55	7.53	8.07	8.20	8.29	8.17	7.84	....
407	8.35	8.30	8.27	Dry.	Dry.	Dry.	8.35	Dry.	Dry.	8.30	8.77	8.70	8.80	8.47	....
406	8.77	8.74	8.70	Dry.	Dry.	Dry.	8.84	Dry.	Dry.	8.97	9.24	9.26	9.20	9.01	....
405	9.53	9.50	9.53	9.44	9.36	9.28	9.62	9.17	9.10	10.06	10.01	9.98	9.63	9.64	....
404	(?) 8.63	10.31	10.33	10.22	10.16	10.08	10.30	10.00	9.99	10.64	10.67	10.58	10.56	10.37	....
403	....	10.76	10.78	10.68	10.56	10.53	10.69	10.41	10.31	10.78	10.94	10.97	10.97	10.87	....
402	11.68	11.45	11.43	11.28	11.31	11.23	11.32	11.10	10.98	11.16	11.46	11.66	11.61	11.57	....
401	....	12.43	12.40	12.37	12.32	12.27	12.35	12.15	12.13	12.31	12.55	12.63	12.64	12.67	....
217	13.28	13.25	13.27	13.23	13.18	13.11	13.25	12.95	(?) 11.43	13.12	13.35	....	13.43	....	13.31
410	13.43	13.43	13.41	13.35	13.20	13.24	13.42	13.08	13.07	13.40	13.62	....	13.55	....	13.41
411	13.55	13.53	13.58	13.48	13.42	13.37	13.58	13.24	13.24	14.01	13.95	....	13.63	....	13.49
412	13.62	13.66	13.72	13.60	13.56	13.50	13.71	13.41	13.44	14.47	14.32	....	13.82	....	13.54
413	....	....	....	....	13.98	13.91	14.01	13.90	13.81	14.06	14.06	....	14.06	....	13.97
503	....	....	....	....	7.61	7.69	8.03	7.75	7.67	8.43	8.44	8.41	8.23	8.08	....
504	....	....	....	....	9.68	9.62	9.87	9.53	9.48	10.39	10.50	10.13	10.14	10.00	....
505	....	....	....	....	9.81	9.73	9.98	9.61	9.69	10.41	10.39	10.25	10.23	10.03	....
506	....	....	....	....	8.16	8.09	8.44	7.99	8.03	8.79	8.87	8.85	8.81	9.04	....
603	....	....	....	....	....	11.02	11.35	11.08	11.16	11.86	11.98	11.81	11.82	11.68	....
604	....	....	....	....	....	11.90	11.92	11.83	11.81	11.79	11.99	12.13	12.23	12.28	....
605	....	....	....	....	....	10.64	10.72	10.44	10.39	10.73	10.90	11.02	11.07	11.03	....

Exhibit 96.—*Elevations of water table at special wells, May 22 and 24, 1922*

Well No.	May 22	May 24	Well No.	May 22	May 24
a	7.22		213		13.23
b	7.14		215		13.07
c	6.69		216		13.20
d	8.66		313		13.12
e	11.22		314		13.12
115		13.22	315		12.91
113		13.36	316		12.88
114		13.39	f		10.86

It is not certain from the data available that the rises are sharp and quick in response to the rain or whether there is a gradual wave of rise from the pond toward the shore, accelerated by the increased gradient near shore and by the increased head. Some rain probably reaches the ground water through percolation on the depression areas, and causes a quick rise in level of the water in near-by wells. Such a rise, however, may occur and be lost within a few hours and not be detected if the measurement of depth to water happens to be taken the next day or even two or more hours later.

There are probably minor fluctuations of the water table due to varying amounts of evaporation. Such fluctuations would be temporary and probably local. It is believed that during the day when evaporation is at a maximum the water table is depressed under the surface depressions and that during the night these depressions flatten out.

As discussed above (see pp. 162–163) near shore there are probably regular fluctuations of water level caused by the tides. This can not be stated positively without proof of measurement, but it seems improbable that the change of 9 feet in base level could occur without a change in the water level. Further, the high chloride content of the water of wells near shore and the wide variation in amount would seem to indicate a tidal influence. On April 20 depths to water were measured at 9 a. m., approximately low tide, and at 3 p. m., approximately high tide. Only four of the wells showed a difference. The results are shown in table below.

Exhibit 97.—*Depths to water*

Well No.	9 a. m.	3 p. m.	Change	Well No.	9 a. m.	3 p. m.	Change
	Feet	*Feet*	*Feet*		*Feet*	*Feet*	*Feet*
409	4.81	4.83	+0.02	404	2.59	2.63	+.04
408	5.04	5.04		403	4.33	4.35	+.02
407	6.33	6.33		402	4.93	4.93	
406	6.35	6.36	+.01	401	4.71	4.71	
405	4.59	4.59					

The differences found are so small they could be within the possible error of measurement. The depths were measured with a steel tape by hand. The measurements can be made very accurately, however, as the reference mark is on each well, and the wells are of such size that it can easily be seen when the mirror of water is broken by the lead sinker on the tape. The fact that the measurements on April 20 showed little or no difference at high or low tide is not conclusive. Any tidal influence may have a lag, and more data would be necessary before any definite statement of no effect can be made.

CALCULATED VELOCITY

The rate of movement of water through sand at a given temperature is determined by the permeability of the sand and the hydraulic gradient. The permeability depends chiefly upon the effective size of grain and the porosity. It can be expressed quantitatively by a transmission constant which is defined by Slichter (1905, 77), as the amount of water transmitted in unit time through a cylinder of sand of unit length and unit cross section under unit difference in head at the ends. For example, if a column of sand 1 square foot in cross section and 1 foot in length will transmit 1 cubic foot of water a minute under a difference in head of 1 foot the transmission constant is 1.

Using the figures for the porosity and effective size of grain obtained for the average Fort Caswell sands, the theoretical rate of movement of the ground water through the sands at trench 500 can be calculated. The average porosity was found to be 48 per cent and the effective size of grain 0.14 mm.

The hydraulic gradient at trench 500, based on levels taken at wells 505 and 503 on May 22, was 1 foot in 115 feet, or 0.9 per cent. Using Slichter's (1905, 13) graphical method shown on Plate II of Water-Supply Paper 140, the transmission constant obtained is 0.4 cubic foot per day. Correcting this figure for the average temperature of 71° F., according to Slichter's (1905, 13) Table II, the transmission constant obtained is 0.468 cubic foot per day. With 48 per cent porosity, this gives a velocity of 0.975 foot per day, or 29.25 feet per month of 30 days. In the uranin experiment at trench 500 (see pp. 22–32), the pit was dosed April 24, and on May 24, 30 days later, the record of farthest distance reached by the uranin was 23 feet. The close agreement is of course accidental.

The rate of movement of ground water varies greatly with diversity in the rocks and differences in pressure gradient. According to experiments and calculations by Slichter, with a pressure gradient of

10 feet per mile the rate is 53 feet per year in fine sand, 845 feet per year in coarse sand, and 5,386 feet, or about a mile, per year, in fine gravel. In tests made by the United States Geological Survey in gravelly deposits in California, Kansas, and Nebraska the velocity was found to range from about 1 foot to about 50 feet per day, and in sandy and gravelly deposits on Long Island from practically zero to about 100 feet per day. In tests in gravelly deposits in Arizona the maximum velocity was found to be 420 feet per day. The average velocity is doubtless much smaller in the deeper and less pervious aquifers than in the surface deposits that have been tested.[8]

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[8] Meinzer, O. E., 1918, Chapter on Water Supply in Military Geology and Topography. From Yale University Press, New Haven, pp. 133, 134.